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Compact Colour Mixing and Collimating Optics for a Multi-Chip Lighting Module

DESCRIPTION

FIELD OF THE INVENTION

[Para 1] The present invention pertains to an integral optical design for light sources and in particular to efficient light extraction, colour mixing and collimation of light emitted by a dense arrangement of white or colour solid state light sources.

BACKGROUND

[Para 2] Present optical designs do not optimally address compactness or integration of LED based luminaires. Today's solutions utilize single colour LED packages and typically only provide primary optics to which secondary or optional tertiary optical systems have to be added to meet the functional requirements. This modular method leads to difficulties in beam collimation, colour mixing and efficiency that can only be overcome with bulky additions making the overall optical design complicated and costly.

[Para 3] Only a few multi-colour solutions exist that integrate more than one LED in a single package, for example, ENLUX or Seoul semiconductor packages. However, these solutions do not effectively address beam collimation or colour mixing and cannot provide a satisfactory solution in one single component. The technical challenge is to achieve sufficient colour mixing and beam collimation at high efficiency.

[Para 4] Most LED manufacturers supply components that incorporate one LED die which is encapsulated and provided with a simple primary optic of very limited utility for lighting purposes. Only some manufacturers supply multi-colour LED packages but none of these packages attempt to maximize light extraction efficiency as this can potentially compromise the thermal performance of the package.

[Para 5] Both United States Patent No. 6,200,002 and U. S. Patent No. 6,547,416 address optical designs for effective colour mixing to generate a light beam having chromaticity and illuminance cross sectional profiles of sufficient homogeneity. However, neither addresses issues of packaging density. In consequence, these designs can only generate light beams which have inferior brightness and additionally require optical systems with considerably bigger dimensions.

[Para 6] United States Patent No. 4,964,025 describes an asymmetrical flux extraction cup for an LED illumination lamp that has an asymmetrical limited viewing angle or cutoff angle. The cup has a

flat section in the bottom normal to the optical axis, for attachment of the LED. In a cross section of one side of the cup, there is a circular section extending from the flat section to a lower point located at an intersection with a line from the opposite cup lip through a nearest edge point of a top surface of an envelope in which the LED is positioned. Next is a lower parabolic section extending from the lower point to an upper point located at an intersection with a projection of the top surface of the positioning envelope. The lower parabolic section has a vertex at the lower point, an axis projecting through the nearest edge point and the lower point, and a focus at the nearest edge point. Then there is an upper parabolic section extending from the upper point to the cup lip. The upper parabolic section has a vertex at the cup lip, an axis extending through the farthest edge point and parallel to the axis of the lower parabolic section, and a focus located at the farthest edge point of the top surface of the positioning envelope.

[Para 7] United States Patent No. 6,644,841 describes a reflector for use with light emitting devices. Multiple reflective surfaces redirect light emission components of the light emitting device, for example a light emitting diode, into a desired direction. The different light emission components including a total internal reflection light emission component. Paired light emitting devices share common reflector surfaces creating an oval light pattern. Holes in the reflector accommodate electrical components and enhance heat dissipation. A deflector pattern on non-reflector surfaces minimizes sun phantom effect when the reflector is used, for example, in a traffic signal.

[Para 8] United States Patent No. 5,921,652 describes light emitting panel assemblies including light emitting panel members and one or more light sources positioned/embedded in a light transition area, which increases the efficiency of light entering the panel members along the light input area to be emitted from one or more light emitting surfaces along the length of the panel members. Light may be reflected or refracted by a surface which changes the path of a portion of light such that it enters the input area of the panel member at a more acceptable angle. A uniform light output distribution may be produced by utilizing a pattern of light extracting deformities.

[Para 9] United States Patent No. 5,758,951 describes arrays of vertical cavity surface emitting lasers ("VCSEL"s) used for illumination in both infra-red and visible light wavelengths. By using several different arrays, each array generating light of a different wavelength, a replacement for conventional lighting sources can be obtained. The present invention offers lower power consumption and longer operating lifetime than known lighting technologies.

[Para 10] United States Patent No. 6,525,464 describes a stacked light-mixing LED which includes a main body, more than one connecting parts, a first chip, and a second chip. Two lights with different wavelength in the visible light spectrum area, such as the yellow light and the blue light, or

the green light and the red light, are respectively excited and emitted from the first chip and the second chip. By controlling electrical current and voltage, the two lights respectively excited from the first chip and the second chip can be symmetrically mixed into another wavelength of light in the visible light spectrum area, such white light.

[Para 11] United States Patent No. 5,803,579 describes an illuminator assembly having a plurality of LEDs on a vehicular support member in a manner such that, when all of the LEDs are energized, illumination exhibiting a first perceived hue, e.g., blue-green, and projected from at least one of the LEDs overlaps and mixes with illumination exhibiting a second perceived hue, e.g., amber, which is distinct from said first perceived hue and which is projected from at least one of the remaining LEDs in such a manner that this overlapped and mixed illumination forms a metameric white color and has sufficient intensity and color rendering qualities to be an effective illuminator.

[Para 12] Therefore there is a need for a new compact multi-chip lighting module with colour mixing and collimating optics.

[Para 13] This background information is provided to reveal information believed by the applicant :o be of possible relevance to the present invention. No admission is necessarily intended, nor should ɔe construed, that any of the preceding information constitutes prior art against the present nvention.

;UMMARY OF THE INVENTION

Para 14] An object of the present invention is to provide a compact colour mixing and collimating ptics for a multi-chip lighting module. In accordance with an aspect of the present invention, there : provided a lighting module comprising: a plurality of light-emitting elements for generating light aving one or more colours, said light-emitting elements positioned into a closely packed array; a ·imary optical system in optical communication with the plurality of light-emitting elements, said ·imary optical system providing a means for light extraction from the plurality of light-emitting ements; and a secondary optical system in optical communication with the primary optical system, id secondary optical system for mixing and collimating the light extracted from the light-emitting ɜments.

IEF DESCRIPTION OF THE FIGURES

ara 15] Figure 1A illustrates a light-emitting element configuration comprising one red, two ːen, and one blue light-emitting elements aligned on a substrate according to one embodiment of : present invention.

[Para 16] Figure 1B illustrates a light-emitting element configuration comprising one red, one green, one blue, and one amber light-emitting elements aligned on a substrate according to another embodiment of the present invention.

[Para 17] Figure 1C illustrates a light-emitting element configuration comprising four white light-emitting elements aligned on a substrate according to a further embodiment of the present invention.

[Para 18] Figure 1D illustrates a light-emitting element configuration comprising two red, three green, one blue, and one amber light-emitting elements aligned on a substrate according to another embodiment of the present invention.

[Para 19] Figure 1E illustrates a light-emitting element configuration comprising one green, and one blue light-emitting elements, and six white light-emitting elements aligned on a substrate according to another embodiment of the present invention.

[Para 20] Figure 2A illustrates an elevated cross sectional view of a primary optical system of a lighting module according to one embodiment of the present invention.

[Para 21] Figure 2B illustrates an elevated cross sectional view of another primary optical system of a lighting module according to one embodiment of the present invention.

[Para 22] Figure 2C illustrates an elevated cross sectional view of another primary optical system of a lighting module according to one embodiment of the present invention.

Para 23] Figure 2D illustrates an elevated cross sectional view of a primary optical system of a ghting module according to one embodiment of the present invention.

Para 24] Figure 2E illustrates an elevated cross sectional view of a primary optical system of a ghting module according to one embodiment of the present invention.

Para 25] Figure 2F illustrates an elevated cross sectional view of a primary optical system of a ghting module according to one embodiment of the present invention.

ara 26] Figure 2G illustrates an elevated cross sectional view of part of a carrier and an tached lighting module according to one embodiment of the present invention.

ara 27] Figure 3A illustrates a circular, a triangular, a square, a hexagonal, and an octagonal ape of a perpendicular cross section of a light-pipe or light-guide acting as a secondary optical stem according to one embodiment of the present invention.

ara 28] Figure 3B illustrates elevated cross sectional views of secondary optical systems cording to one embodiment of the present invention.

ara 29] Figure 3C illustrates elevated cross sectional views of secondary optical systems cording to another embodiment of the present invention

[Para 30] Figure 4A illustrates an elevated side view of two lighting modules, each having a separate primary and a secondary optical system according to one embodiment of the present invention

[Para 31] Figure 4B illustrates an elevated side view of a system comprising two individual primary optical systems and two individual secondary optical systems integrated into one element and a common tertiary optical system according to one embodiment of the present invention.

[Para 32] Figure 4C illustrates an elevated cross-sectional view of a system comprising two individual primary optical systems and a common single integrally formed body providing a secondary optical system according to one embodiment of the present invention.

[Para 33] Figure 5A illustrates an elevated cross sectional view of a lighting module according to an embodiment of the present invention according to one embodiment of the present invention.

[Para 34] Figure 5B illustrates a perpendicular cross section of the lighting module as illustrated in Figure 5A having a substantially circular shape.

[Para 35] Figure 5C illustrates a perpendicular cross section of the lighting module as illustrated in -igure 5A having a substantially square shape.

Para 36] Figure 6A illustrates an elevated cross sectional view of a lighting module according to ınother embodiment of the present invention.

Para 37] Figure 6B illustrates a perpendicular cross sections through the secondary optical ystem as illustrated in Figure 6A having a circular shape.

Para 38] Figure 6C illustrates a perpendicular cross sections through the secondary optical ystem as illustrated in Figure 6A having a hexagonal shape.

Para 39] Figure 7A illustrates an elevated view of a lighting module according to an embodiment the present invention in which the secondary optical system of the lighting module comprises a ulti-functional solid optical element according to one embodiment of the present invention.

ara 40] Figure 7B illustrates the perpendicular cross section of the embodiment illustrated in jure 7A.

ara 41] Figure 8 illustrates an elevated cross sectional view of a lighting module according to other embodiment of the present invention.

ara 42] Figure 9 illustrates a cross sectional view of a primary optical system according to other embodiment of the present invention.

ara 43] Figure 10 illustrates a perspective view of a secondary optical system component cording to another embodiment of the present invention.

[Para 44] Figure 11A illustrates a bottom view of the secondary optical system component of Figure 10.

[Para 45] Figure 11B illustrates a cross sectional view of the secondary optical system component of Figure 11A taken along line A-A.

[Para 46] Figure 11C illustrates a cross sectional view of the secondary optical system component of Figure 11A taken along line B-B.

[Para 47] Figure 12 illustrates a perspective view of the secondary optical system formed from a plurality of secondary optical system components of Figure 10.

[Para 48] Figure 13 illustrates a perspective view of a portion of the secondary optical system of Figure 12.

[Para 49] Figure 14 illustrates a perspective view of a tertiary optical system according to another embodiment of the present invention.

[Para 50] Figure 15 illustrates an exploded view of an optical system for a lighting module according to one embodiment of the present invention, wherein the optical system comprises the secondary optical system of Figure 12 and a plurality of tertiary optical systems of Figure 14.

DETAILED DESCRIPTION OF THE INVENTION

[Para 51] Definitions

[Para 52] The term "light-emitting element" is used to define any device that emits radiation in any region or combination of regions of the electromagnetic spectrum for example, the visible region, infrared and/or ultraviolet region, when activated by applying a potential difference across it or passing a current through it, for example. Therefore a light-emitting element can have monochromatic, quasi-monochromatic polychromatic or broadband spectral emission characteristics. Examples of light-emitting elements include semiconductor, organic, or polymer/polymeric light-emitting diodes, optically pumped phosphor coated light-emitting diodes, optically pumped nano-crystal light-emitting diodes or any other similar light-emitting devices as would be readily understood by a worker skilled in the art. Furthermore, the term light-emitting element is used to define the specific device that emits the radiation, for example a LED die, and can equally be used to define a combination of the specific device that emits the radiation together with a housing or package within which the specific device or devices are placed.

[Para 53] The term "chromaticity" is used to define the perceived colour impression of light as it is perceived by a human observer according to standards of the Commission Internationale de l'Eclairage.

[Para 54] The term "luminous flux output" is used to define the quantity of luminous flux emitted by a light source according to standards of the Commission Internationale de l'Eclairage.

[Para 55] The term "luminous intensity" is used to define the quantity of luminous flux per unit solid angle emitted by a light source according to standards of the Commission Internationale de l'Eclairage and is typically measured in candela.

[Para 56] The term "luminance" is used to define quantity of luminous flux per unit solid angle and unit area of a light source as it is perceived by a human observer according to standards of the Commission Internationale de l'Eclairage and is typically measured in lumen/steradian/cm^2.

[Para 57] The term "gamut" is used to define the plurality of chromaticity values that a light source can achieve.

[Para 58] As used herein, the term "about" refers to a +/-10% variation from the nominal value. It is to be understood that such a variation is always included in any given value provided herein, whether or not it is specifically referred to.

[Para 59] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

[Para 60] The present invention provides a compact format lighting module that can provide a desired level of mixing and collimating of light generated by multiple light-emitting element chips within the luminaire module. The lighting module comprises a plurality of light-emitting elements for generating light having one or more colours, wherein the light-emitting elements are configured into a closely packed array. The module further comprises a primary optical system enabling light extraction from the light-emitting elements to which it is optically coupled. A secondary optical system that is optically coupled to the primary optical system is additionally integrated into the lighting module. The secondary optical system is configured to be compatible with the primary optical system and provides a means for mixing and collimating the light extracted from the plurality of light-emitting elements. Furthermore, the primary optical system may be integral to the secondary optical system. The lighting module may further comprise a tertiary optical system to further manipulate the light after interaction with the secondary optical system.

[Para 61] The optical design of the present invention can be utilized in lighting systems to effectively generate adjustable white or coloured light with high optical efficiency. Moreover, the optical design utilizes a combination of different white or colour light-emitting elements in a highly effective compact luminaire module design. The lighting module can comprise light-emitting elements which can emit light in different wavelength regimes. Examples for wavelength regimes are red, green, blue, and/or amber or other desired wavelength regimes as would be readily understood.

The lighting module design enables colour mixing and beam collimation. The light-emitting elements in the lighting module can be dimmed such that the lighting module can generate light of independently controllable chromaticity and luminous flux output. The chromaticity of the lighting module can be controlled to generate white light within a predetermined range of correlated colour temperatures (CCT) or it can be controlled to generate any colour within the gamut of the lighting module.

[Para 62] The lighting module can provide effective and efficient light extraction, colour mixing, beam shaping and collimation in an integral design. It takes into account the module geometry, the placement of the light-emitting elements, and the integration of the optical components.

[Para 63] Positioning of Light-Emitting Elements

[Para 64] The lighting module design utilizes closely packaged light-emitting elements, for example, densely mounted LED dies on a substrate. A high packing density of the light-emitting elements can provide for a higher average luminance and reduced Etendue at a smaller input aperture of the lighting module. As a result the lighting module, and in consequence, a luminaire for example, can be more compact, require fewer and smaller optical components and can achieve better collimation within the same mechanical envelope as conventional systems based on individual LED packages. Moreover, light originating from densely packed different colour sources can be more easily mixed into a light beam of desired chromaticity substantially uniformity of the luminous intensity distribution and of desired chromaticity uniformity at the exit aperture of the lighting module. Portions of the optical system of the luminaire module can serve as a housing to encapsulate the light-emitting elements and protect them from environmental conditions.

[Para 65] The lighting module can comprise one or more light-emitting elements. The relative placement of the light-emitting elements and the optical system is important and can strongly affect the effectiveness and efficiency of the lighting module. Closely arranging the light-emitting elements can improve mixing and reduce optical losses of the emitted light but can also increase thermal stress which may require a thermal management system.

[Para 66] In one embodiment, one or more red, green, and blue, or red, green, blue, and amber light-emitting elements can be arranged in a two-dimensional lattice, for example, in a square, circular, hexagonal lattice, or it can be arranged in any other regular, pseudo-regular, or irregular fashion on surfaces of any shape. For example, the specific arrangement of light-emitting elements can maximize luminance and reduce Etendue by reduction of spacing between the light-emitting elements. Furthermore specific arrangement can ensure that the individual colours are evenly distributed such that chromaticity uniformity of the intensity distribution and consequently

chromaticity uniformity over a plane illuminated by the lighting module is achievable. For example, it can be beneficial for achieving a homogeneous chromaticity, when the arrangement of light-emitting elements for each colour has zero total colour momentum relative to the optical axis in axial symmetrical optical systems. The colour momentum of a light source can be defined as the product of its chromaticity, its luminous flux and its distance relative to the origin of a chosen coordinate system, and the total colour momentum is the sum of these products over all light-emitting elements of the same colour.

[Para 67] Figures 1A, 1B and 1C illustrate light-emitting element configurations according to embodiments of the present invention. Figure 1A illustrates an alignment of one red light-emitting element, two green light-emitting elements, and one blue light-emitting element as it can be affixed on a substrate. Figure 1B illustrates an alignment of one red, one green, one blue, and one amber light-emitting elements as it can be affixed on a substrate. Figure 1C illustrates and alignment of four white light-emitting elements as it can be affixed on a substrate. Figure 1D illustrates an alignment of two red and three green light-emitting elements, and one blue and one amber light-emitting elements as it can be affixed on a substrate. Figure 1E illustrates and alignment of one green, and one blue light-emitting elements, and six white light-emitting elements as it can be affixed on a substrate. The dashed line **111, 121, 131, 141** and **151** indicate the size and substantially square, circular, square, octagonal and hexagonal cross section, respectively of the entrance aperture of the corresponding optical system. It is understood that the optical design of the lighting module can have any other arrangement of any other number of colour or white light-emitting elements.

[Para 68] Primary Optical System

[Para 69] The lighting module comprises a primary optical system enabling light extraction from the light-emitting elements to which it is optically coupled. The primary optical system can include one or more refractive elements, for example, a dome lens per one or more light-emitting elements, or a micro-lens array having one lenticular element per each or more light-emitting elements or a micro-lens array having more than one lenticular element for each light-emitting element. The refractive element can be a solid glass or plastic or a fluid optical element. Furthermore the primary optical system can also comprise one or more diffractive or holographic elements, or one or more diffusive or specular reflective elements. In one embodiment, the primary optical system can be specifically tailored to the luminance distribution of the corresponding light-emitting elements to increase light extraction.

[Para 70] In one embodiment the primary optical system can comprise an index matching encapsulation material. To improve light extraction, the light-emitting elements can be encapsulated

in a transparent material with a predetermined optical refractive index. For example, the transparent material can be an optical silicone and have a refractive index of 1.4 to 2 or higher. The optical refractive index of the material can be chosen to match the index of refraction of, for example, the LED dies. However, commercially available material with suitable optical properties exhibit refractive indices of 1.4 to 1.6, which can be significantly lower than the refractive indices of the material used to manufacture the light-emitting elements, for example semiconductor material. Alternatively the encapsulation can have a predetermined thickness and optical refractive index to increase light extraction. The surface of the die can be coated with a layer of encapsulation material of a determined thickness and optical refractive index creating anti-reflective coating comparable to anti-reflective coatings used in optics manufacturing.

[Para 71] In one embodiment the encapsulation material can be patterned or textured, for example, sanded, embossed, stamped, or otherwise structured or microstructured. In one embodiment the encapsulation material may be shaped like a dome lens or a micro-lens array by a stamping or casting or moulding process thereby eliminating the need for a glass or plastic lens serving the same function.

[Para 72] Figures 2A, 2B, 2C, 2D, 2E, 2F, 2G and 9 illustrate elevated cross sections of a primary optical system according to embodiments of the present invention. Figure 2A illustrates an elevated cross sectional view of a primary optical system of a lighting module comprising a dome lens **311** optically communicating with two or more light-emitting elements **313**. Figure 2B illustrates an elevated cross sectional view of a primary optical system of a lighting module comprising one dome lens **321** for each of one or more light-emitting elements. Figure 2C illustrates an elevated cross sectional view of a primary optical system of a lighting module comprising a micro lens array **331** optically communicating with two or more light-emitting elements. Figure 2D illustrates an elevated cross sectional view of a primary optical system of a lighting module comprising a dome lens optically communicating with two or more light-emitting elements which can have a lateral reflector element **345** circumscribing the light-emitting elements. Figure 2E illustrates an elevated cross sectional view of a primary optical system of a lighting module comprising an optical encapsulating material having a textured or embossed surface or interface **357**. The encapsulation material may be a material with high refractive index and can be embossed or textured by ways well known to someone skilled in the art. Figure 2F illustrates an elevated cross sectional view of a primary optical system of a lighting module comprising a fluid lens **361** with controllable focal length. The fluid lens can be made of, for example, one or more electro active materials which can be designed to adapt their shape according to an applied electrical field. For example, the focal length can be controlled by applying a voltage to

one or more electrodes **369** positioned within the primary optical system. The one or more electrodes can be connected to a controller which can apply and control the voltage between them to create a required electrical field under which the one or more electro active materials shape to form a refractive optical element of adjustable focal length. It is understood that a variable focal length lens can be achieved by utilizing material that changes its refractive index within an electrical field such as a liquid crystal material thereby achieving variable focal length due to refractive index changes within the material instead of a change in shape. Figure 2G illustrates an elevated cross sectional view of part of a carrier **372** and an attached primary optic of a lighting module **370**. The assembly comprises one or more light-emitting elements **373** mounted to a substrate **374**, encapsulated by refractive index matching material **376**, covered by a dome lens **371** and surrounded by an insert **378**. The insert can have a reflective surface facing the light-emitting elements.

[Para 73] It is understood, that each of the lighting modules as illustrated in Figures 2A to 2G can comprise encapsulation material which can be optically active.

[Para 74] In one embodiment of the present invention, the primary optical system can comprise a light pipe system which can be optimally coupled to the encapsulation material.

[Para 75] In one embodiment of the present invention, the primary optical system is integrated into the secondary optical system.

[Para 76] **Secondary Optical System**

[Para 77] The lighting module further comprises a secondary optical system. The secondary and the primary optical system can be coupled to minimize light loss between the two systems. The secondary optical system can provide colour mixing functionality, which can be required in lighting modules with multi-colour light-emitting elements. The secondary optical system can generate a light beam of substantially uniform chromaticity over substantially the entire intensity distribution which can be suitable for illuminating objects at a predetermined distance with light of a predetermined chromaticity or CCT. Furthermore, the secondary optical system can generate a light beam of substantially uniform chromaticity across the exit aperture of the lighting module. In addition, the secondary optical system can facilitate beam shaping and can collimate the light beam into a predetermined distribution, for example, for spotlight applications a Gaussian or top hat intensity profile of 20° FWHM (full width at half maximum).

[Para 78] The secondary optical system can comprise one or more reflective and/or refractive optical elements, for example, solid or hollow light pipes or light guides for the transmission of light. The optical elements can have predetermined axial or perpendicular cross sections. The secondary optical system can comprise refractive elements, for example, one or more lenses, Fresnel lenses,

lens arrays, tandem lens arrays, diffractive and holographic elements. It can also comprise diffuser elements or fluid lenses with variable focal lengths to control beam distribution and collimation. In one embodiment the secondary optical system comprises a hollow or solid lightpipe. This secondary optical system can be designed to minimize the number of times light is reflected when transmitted through this optical system and still provide mixing or randomization of light to provide uniform chromaticity distributions. It is understood that each reflection reduces the light intensity by a reflectivity factor R and therefore after N reflections with the same reflectivity factor R the total reflected intensity I_N can be expressed in terms of the original intensity I_0 and can be evaluated based on the following:

$$I_N = I_0 \cdot R^N \qquad (1)$$

[Para 79] The secondary optical system can have a reflective wall surface of predetermined perpendicular and axial cross sectional profile that extends between an entrance aperture and an exit aperture. The wall surface can assist with beam shaping and colour mixing. It is understood, that the cross section of the surface can have an axial symmetric shape or it can have any other desired shape. The surface can flare or taper towards the exit aperture. For example, axially symmetrical systems with square, hexagonal or octagonal perpendicular cross sections can more effectively mix and randomize light than circular or triangular wall structures. Consequently, this form of secondary optical system can provide better randomization and can have more compact dimensions.

[Para 80] It is understood, that the cross sectional shape of, for example, an axially symmetric light pipe can determine the collimation properties of a beam. For example, the length and flare angle of a light pipe can optimize the efficiency of the luminaire. Generally, the shape of the reflective wall, for example, its axial profile for an axial symmetric reflective wall, can determine the effectiveness of the secondary luminaire system. For example, the profile can be characterized by its entrance aperture size, exit aperture size, length, and curvature.

[Para 81] In one embodiment the curvature of the profile can be parabolic, elliptic, or hyperbolic. Alternatively, the profile or the optically active surface can comprise individual straight or curved continuous conical segments.

[Para 82] It is also understood that a part or all of the wall surface, entrance aperture or exit aperture can be optically active. For example, part or all of the wall surface, entrance aperture or exit aperture can be coated in a phosphor.

[Para 83] In one embodiment, the secondary optical system can comprise a refractive element, for example, a dome lens, plano convex lens, a biconvex lens, a Fresnel lens, or a micro lens array

proximal to the output aperture. This element can be an integral part of one of the aforementioned light pipe or light guides, for example. It is understood, that the secondary optical system can also comprise a diffractive, a holographic, a reflective, or a diffusive element proximal to the exit aperture. It is also understood that a diffusive element or aforementioned elements can be placed anywhere along the optical path where it is optically appropriate such as proximal to the entrance aperture of the secondary optical system. Furthermore, any refractive element can also be a controllable variable focal length fluid lens.

[Para 84] In addition, the optical system can be designed to leak or guide a small amount of the luminous flux output to one or more photosensitive elements or one or more extraction elements with one or more attached photosensitive elements. The photosensitive elements can provide information relating to chromaticity or luminous flux output to a control system. For example, these photosensitive elements can be a photo-sensor, photo-diode or other optically sensitive sensor as would be known by a worker skilled in the art.

[Para 85] Figures 3A, 3B and 3C illustrate various cross sectional shapes of secondary optical systems according to embodiments of the present invention. Figure 3A illustrates various embodiments having a circular, a triangular, a square, a hexagonal, and an octagonal cross section perpendicular to the overall light propagation of a secondary optical system, for example, a light-pipe or light-guide. In one embodiment, optical elements of square, hexagonal, or octagonal perpendicular cross section are used because they can more effectively mix light than optical elements of circular or triangular perpendicular cross section. Figures 3B and 3C illustrate four cross sectional views **210, 220, 230, 240** of lighting modules each having different cross sections according to the present invention. Each lighting module comprises a number of light-emitting elements **211** affixed on a substrate **213** and a secondary optical element **215**, for example, an axial symmetric hollow body with a mirrored inside surface extending from the light-emitting elements. Figure 3B illustrates a cylindrical hollow body **215** and a concave axially symmetric hollow body **225**. Figure 3C illustrates a conical hollow body **235** and a polygonal hollow body **245** with the polygon cross section being created by joining of linear segments.

[Para 86] Tertiary Optical System

[Para 87] Following the optical path, the lighting module may comprise a further tertiary optical system in addition to the primary and secondary optical system. It is understood, that the tertiary optical system can be designed to further improve beam shaping of one or more lioghting modules or adjust beam shaping of the lighting module to the required application. In contrast, each of the primary and secondary optical systems are optically active at a lighting module level. The tertiary

optical system can comprise any combination of aforementioned optical elements and can be used to manipulate light emitted from one or more lighting modules.

[Para 88] The invention will now be described with reference to specific examples. It will be understood that the following examples are intended to describe embodiments of the invention and are not intended to limit the invention in any way.

[Para 89] **Examples**

[Para 90] Example 1:

[Para 91] Figures 4A and 4B illustrate a lighting module according to embodiments of the present invention. Figure 4A illustrates an elevated side view of two lighting modules **410**, each having individual primary optical system **411** and secondary optical system **412** but can share a single tertiary optical system, which is not illustrated. The optical system comprises an optical feed back sensor **419**, for example, a photo diode positioned in the center between the lighting modules. Figure 4B illustrates an elevated cross sectional view of a system comprising two separate primary optical systems **421** having one common integrally formed body **422** providing a common secondary optical system. The integrally formed body may allow optical communication to an optical feedback system within the secondary optical system **422**. A tertiary optical system **423** is provided to further manipulate the light emitting from the light modules. An optical feedback sensor **421** can be placed between the two modules and provisions can be made to guide a small portion of light representative of chromaticity and luminous flux output of the system to the sensor. The integrally formed body can contain two or more arrangement modules, for example six modules in a hexagonal arrangement.

[Para 92] Figure 4C illustrates an elevated cross sectional view of part of a lighting module in which the single integrally formed body comprises a secondary optical system **432** which optically couples two primary optical systems, according to one embodiment of the present invention. The lighting module comprises an optical feed back sensor **439** positioned between the primary optical systems and in optical communication with the secondary optical system. The first interface **433** of the secondary optical system on the far side of the light-emitting elements can be shaped to any form required to assist in refractive beam shaping, and it can be textured, embossed or otherwise structured to provide, for example, a Fresnel lens. The second interface **434** of the secondary optical system on the near side of the optical feed back sensor can be shaped to any form to assist in the extraction of light from the primary optics in the sections in proximity to the light emitting elements, to assist in the shaping of the output beam and can be coated and shaped to assist in the extraction of an amount of light from the secondary optical system which is representative of the

total light emitted by the lighting module and sufficient for reliable operation of the sensor element. This second interface can additionally be textured or otherwise structured. The surfaces or interfaces of the secondary optical system can be structured by means well known to one skilled in the art.

[Para 93] Example 2:

[Para 94] Figure 5A illustrates an elevated cross sectional view of a lighting module **500** according to an embodiment of the present invention. The lighting module comprises four light-emitting elements **503**, for example, one red and one blue, and two green or one of each of red, green, amber, and blue colour, which are affixed to a substrate **510**. The light-emitting elements are encapsulated by a refractive index matching material **520**, for example, high refractive index silicone. The light-emitting elements are environmentally sealed by the substrate and the primary optical system. In addition, the primary optical system comprises a dome lens **525**. The lighting module comprises a secondary optical system which has a mirror element **530** with a specular or diffuse reflective inner surface **531** extending from an entrance aperture **540** which widens into an exit aperture **545**. The secondary optical system additionally comprises a refractive optical element **550**, for example, a planar-convex or any other lens, positioned proximal to the exit aperture of the mirror element. In addition, a diffuser element, which is not illustrated, can be positioned before or after the refractive optical element in the optical path. Figure 5B illustrates a perpendicular cross section of the lighting module in which the mirror element has a substantially circular shape. Alternatively, Figure 5C illustrates a perpendicular cross section of the lighting module in which the mirror element has a substantially square shape. The dimensions of the optical system can be compact, for example, about 30 mm tall by about 20 mm across or in diameter.

[Para 95] One or more lighting modules having white or colour light-emitting elements can be operatively attached to a carrier to form a complete lighting system and electrically connected to a controller controlling the chromaticity and luminance of the lighting module through adjustment of the light output of the light-emitting elements.

[Para 96] Example 3:

[Para 97] Figure 6A illustrates an elevated cross sectional view of a lighting module according to another embodiment of the present invention. The lighting module comprises a primary **610** and a secondary **620** optical system similar to the embodiment illustrated in Figure 5A. The light-emitting elements are encapsulated by a refractive index matching material, for example, high refractive index silicone. The lighting module additionally comprises a substrate **630** which is positioned inferior to a carrier **640**, i.e. on the side of the carrier opposite the secondary optical system. The substrate can provide a thermal interface **631** on the side opposite to the side of the substrate to which the light-

emitting elements **601** are affixed. The thermal interface can be thermally connected to a thermal management system which is not illustrated. The lighting module further comprises an insert **650** having a reflective surface facing the light-emitting modules. In this specific embodiment, the carrier is an integral part of the primary optical system as a support member. Figures 6B and 6C illustrate perpendicular cross sections of embodiments of a secondary optical system for use with the lighting module as illustrated in Figure 6A. Figures 6B and 6C illustrate a secondary optical system having a circular and hexagonal cross sectional shape, respectively.

[Para 98] Example 4:

[Para 99] Figure 7A illustrates an elevated view of a lighting module according to an embodiment of the present invention in which the secondary optical system **720** of the lighting module comprises a multi-functional solid optical element **730**. The exit aperture of the refractive element has a macro-structured surface **731** circumscribed by a circumferential surface **732** of, for example, octagonal perpendicular cross section. The refractive element can be designed to provide any desired refractive functionality. It can also have a micro-structured surface that provides, for example, a translucent diffusive character. The input aperture of the solid refractive element can be flat or can be shaped like a negative dome or microlens array, for example. Insertion of encapsulation material with high refractive index into the cavity between LED die and input aperture of the optic can lead to high extraction efficiency and a reduced number of parts. A solid optic can comprise a shaped output aperture as indicated and a shaped input aperture (also indicated in figure 7A) reducing the number of required parts to one optic only in comparison to a hollow optic system. The solid optical element **730** can be made such that the rays propagate by Total Internal Reflection or the wall surfaces can be coated such that high reflectivity is achieved.

[Para 100] The circumferential surface **732** can be specular or diffuse reflective, for example, the surface can be coated with reflective material or its surface can be structured or textured. Figure 7B illustrates a top view of a lighting module having an octagonal cross section according to an embodiment as illustrated in Figure 7A. It is also understood that the elevated cross section as shown in Figure 7A can be parabolic, elliptical, hyperbolic or comprise individual straight or curved continuous conical segments, for example.

[Para 101] It is understood that a lighting module can have an alternatively shaped perpendicular cross section. It is also understood that the refractive element and other optical system components can be affixed to, for example, the substrate or the carrier or a tertiary optical system, via affixing technologies known in the art, which can secure the optical system components in a position relative

to the light-emitting elements which is required for the effective extraction of light emitted by the light-emitting elements.

[Para 102] Example 5:

[Para 103] Figure 8 illustrates an elevated cross sectional view of a lighting module according to another embodiment of the present invention. The lighting module comprises a secondary optical system comprising a reflective element **830** having convex shaped inner reflective surface **831** extending between an entrance and an exit aperture. A Fresnel lens **840** covers the exit aperture which can improve beam collimation under operating conditions. A number of light-emitting elements **801** affixed to a substrate **810** are covered by a refractive index matching material **820** which is covered by a micro lens array element **825** which extends into the entrance aperture. The substrate is affixed to the top of a carrier **870**. It is understood that the inner surface can be specular or diffuse reflective and that its shape can have any form required for effective colour mixing and colimation.

[Para 104] It is further understood that the reflective element **830** can be a hollow body having a reflective inner surface.

[Para 105] Example 6:

[Para 106] Figure 9 illustrates a primary optical system according to one embodiment of the present invention. This primary optical system can be positioned proximate to the light-emitting elements with which it is associated. The primary optical system comprises an outer dome surface **880** and an interior planar surface **882**. The primary optical system can rest on the substrate to which the light-emitting elements are affixed. The pocket proximal to the bottom of the primary optical system can provide room to accommodate the light extracting elements. Encapsulation material such as an optical silicone with suitable refractive index can fill the space between the light-emitting elements and the primary optical system thereby enhancing the optical extraction efficiency. The primary optical system can be optimized for substantially maximum light extraction from the light-emitting elements with which it is optically coupled at substantially a minimal size of the optical clear aperture. Reducing the footprint of the optically clear aperture of the primary optical system (for example the projection of the dome section of the optical element) can reduce the Etendue and increase average luminance for a benefit of collimation and colour mixing for the lighting module. The outer dome surface **880** can provide a high extraction efficiency by reducing Fresnel reflections. Antireflection coating of the outer surface of the outer dome section can further increase extraction efficiency.

[Para 107] Figure 10 illustrates a perspective view of a secondary optical system component according to one embodiment of the present invention, wherein this secondary optical system component comprises the secondary optical system **900** formed as a "cone" having a hexagonal cross sectional shape. The secondary optical system provides a means for light mixing, for example colour mixing, and collimating the light emitted by the light-emitting elements associated therewith. The secondary optical system component further comprises mechanical elements such as **905, 910** and **915** which provides placing the secondary optical system accurately and reproducibly on a carrier to interface with the primary optical system as well as provide a means for connection of multiple secondary optical system components, for example as illustrated in Figures 12 and 13.

[Para 108] Figure 11A is a bottom view of the secondary optical system component illustrated in Figure 10, wherein the light-emitting elements together with the primary optical system are aligned in the entrance aperture **920** defined within the secondary optical system component. Figures 11B and 11C illustrate cross sectional views of the secondary optical system element taken along lines A-A and B-B, respectively and indicate mechanical indexing features. The optical surfaces are displayed cross-hatched and are coated with for example a highly reflective material such as protected aluminium in order to achieve high optical efficiency. The dome section of the primary optical system illustrated in Figure 9 can be inserted into the secondary optical element to capture substantially a maximum of light that is extracted by the primary optical element.

[Para 109] Figure 14 illustrates a perspective view of a tertiary optical element according to one embodiment of the present invention, wherein the tertiary optical element is plano-convex and configured to mate with the hexagonal cross sectional shaped secondary optical system illustrated in Figure 10. It is understood that surfaces of the tertiary optical element can be aspheric, biconvex or tailored to achieve the desired optical performance. It is understood that a diffusive optical element such as a holographic diffuser of desired diffuser level can be attached to the plano side of the lens to aid in the colour mixing. It is also understood that the diffusive properties can be integrated on the lens surface itself and may be included in the lens mould. It is also understood that a diffusive optical element can be placed anywhere along the optical path, for example proximal to the entrance aperture or exit aperture of the secondary optical element. The tertiary optical element can be manufactured from any one or more of a plurality of materials, as would be readily known to a worker skilled in the art.

[Para 110] In one embodiment, antireflection coating of the tertiary optical element can further enhance system efficiency.

[Para 111] In one embodiment, the tertiary optical system provides a means for further blending of the light generated by the light-emitting elements.

[Para 112] In one embodiment as illustrated in Figure 14, the tertiary optical element can comprise an interfacing means **950** which can provide an indexed mating location for an optical element proximate to the tertiary optical element.

[Para 113] Figure 15 illustrates an exploded view of a plurality of secondary optical system components and tertiary optical systems, which can form a portion of an optical system for a lighting module according to one embodiment of the present invention.

[Para 114] It is obvious that the foregoing embodiments of the invention are exemplary and can be varied in many ways. Such present or future variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

What is claimed is:

[Claim 1] A lighting module comprising:

a plurality of light-emitting elements for generating light having one or more colours, said light-emitting elements positioned into a closely packed array;

a primary optical system in optical communication with the plurality of light-emitting elements, said primary optical system providing a means for light extraction from the plurality of light-emitting elements; and

a secondary optical system in optical communication with the primary optical system, said secondary optical system for mixing and collimating the light extracted from the light-emitting elements.

ABSTRACT

The present invention provides a compact format luminaire module that can provide a desired level of mixing and collimating of light generated by multiple light-emitting element chips within the luminaire module. The luminaire module comprises a plurality of light-emitting elements for generating light having one or more colours, wherein the light-emitting elements are configured into a closely packed array. The module further comprises a primary optical system enabling light extraction from the light-emitting elements to which it is optically coupled. A secondary optical system that is optically coupled to the primary optical system is additionally integrated into the luminaire module. The secondary optical system is configured to be compatible with the primary optical system and provides a means for mixing and collimating the light extracted from the plurality of light-emitting elements. Furthermore the primary optical system may be integral to the secondary optical system. The luminaire module may further comprise a tertiary optical system to further manipulate the light after interaction with the secondary optical system.

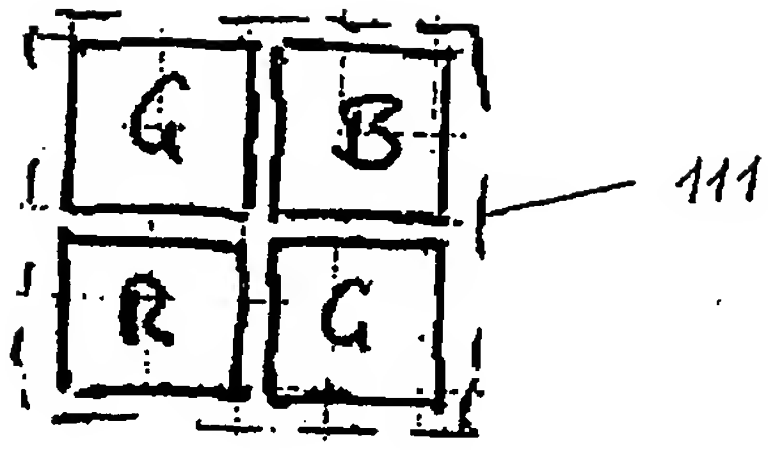

FIGURE 1A

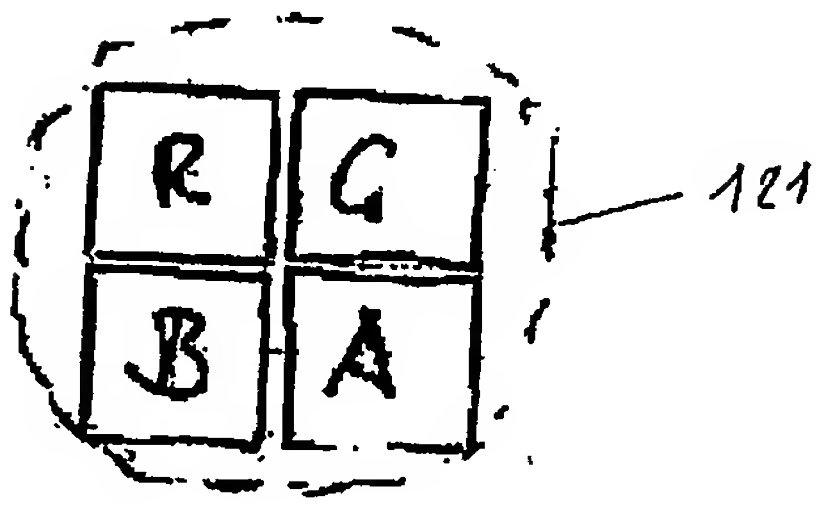

FIGURE 1B

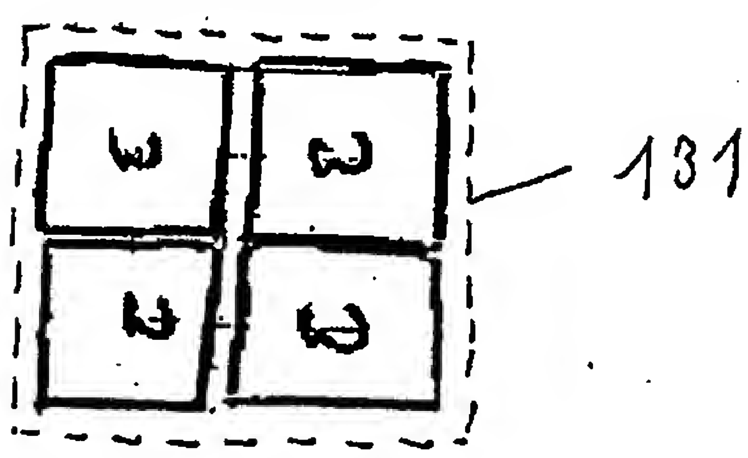

FIGURE 1C

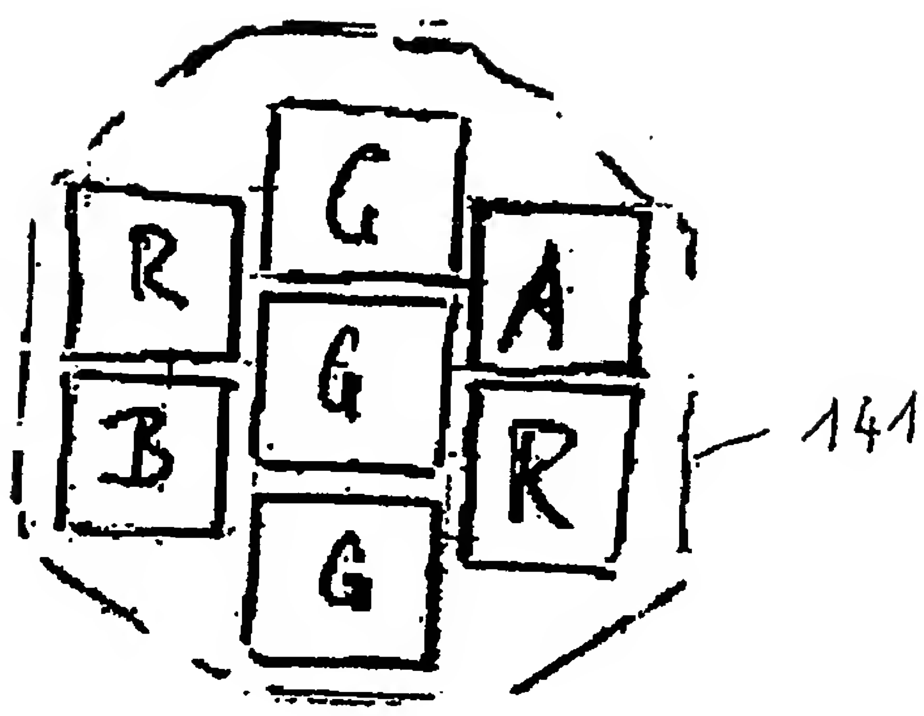

FIGURE 1D

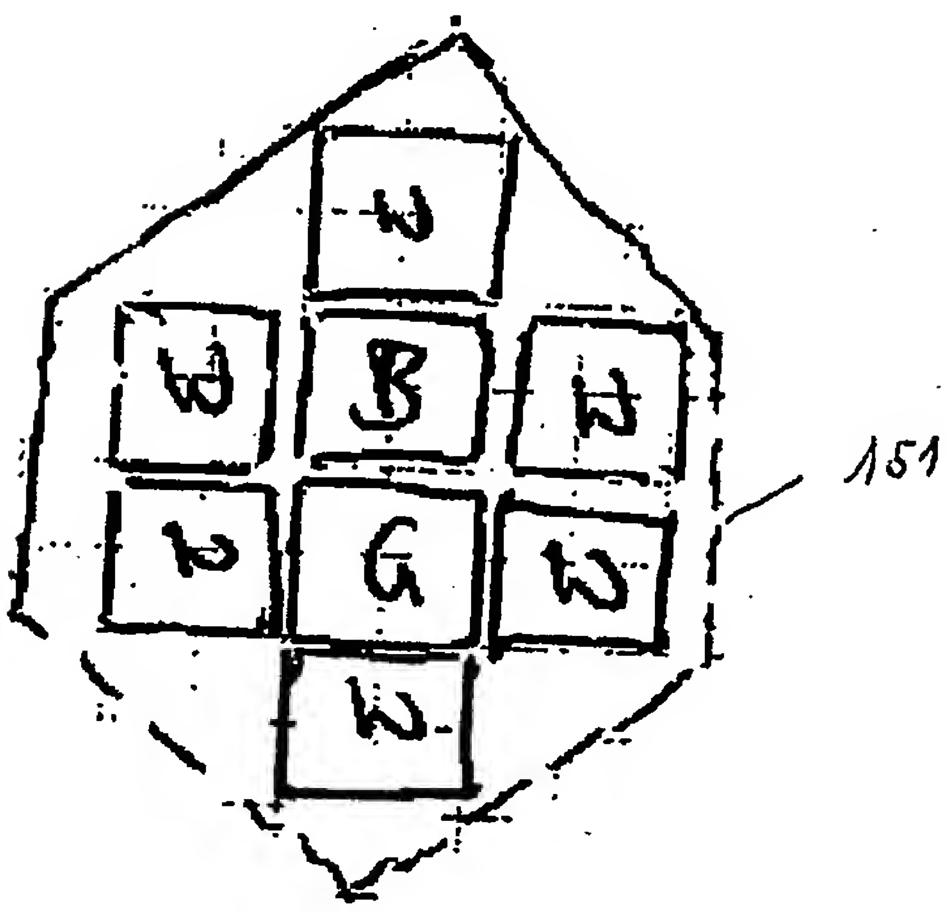

FIGURE 1E

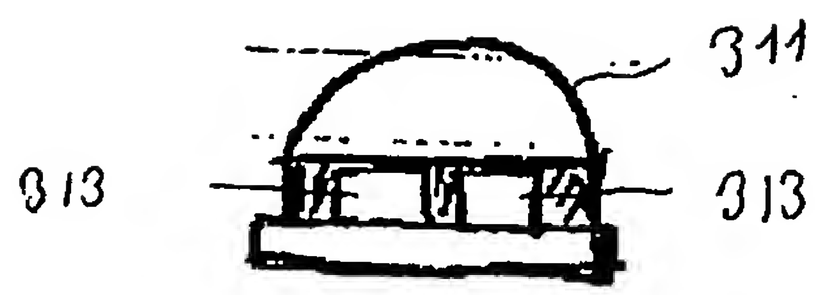

FIGURE 2A

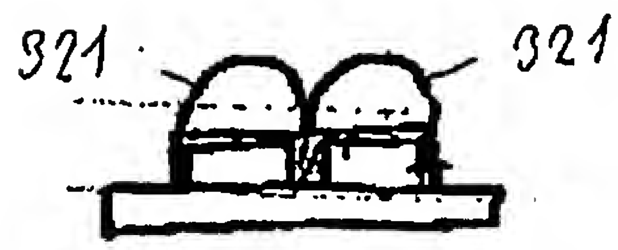

FIGURE 2B

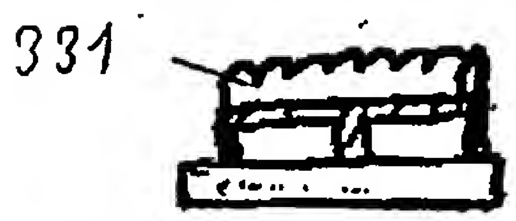

FIGURE 2C

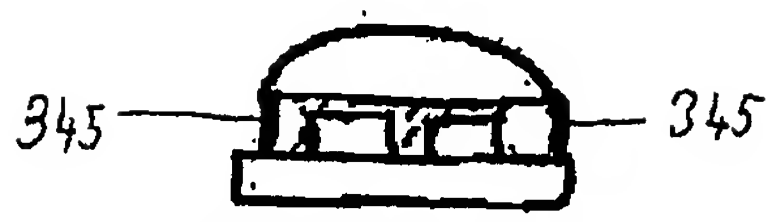

FIGURE 2D

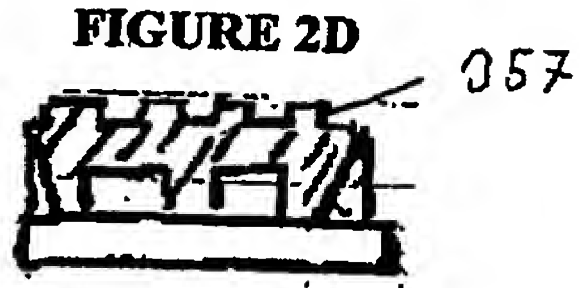

FIGURE 2E

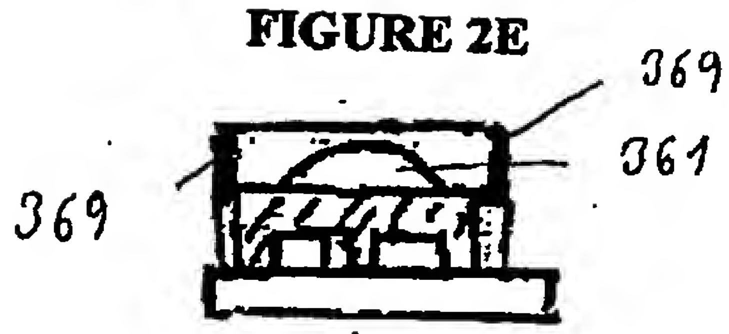

FIGURE 2F

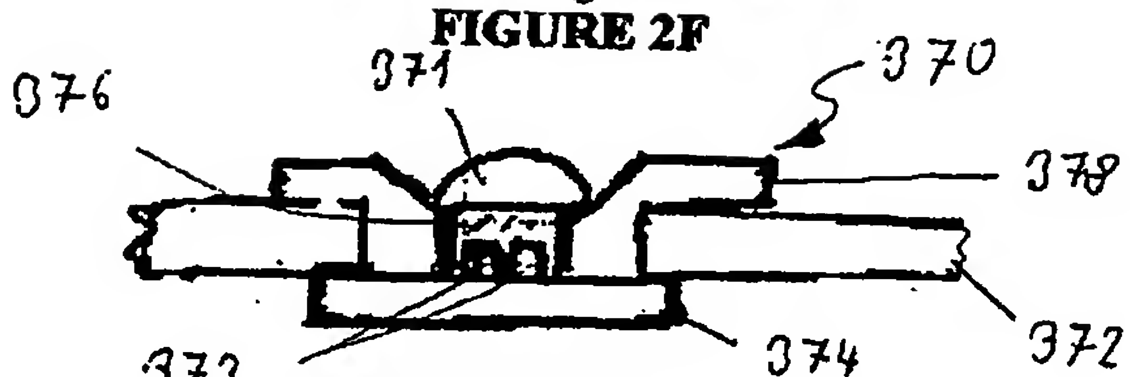

FIGURE 2G

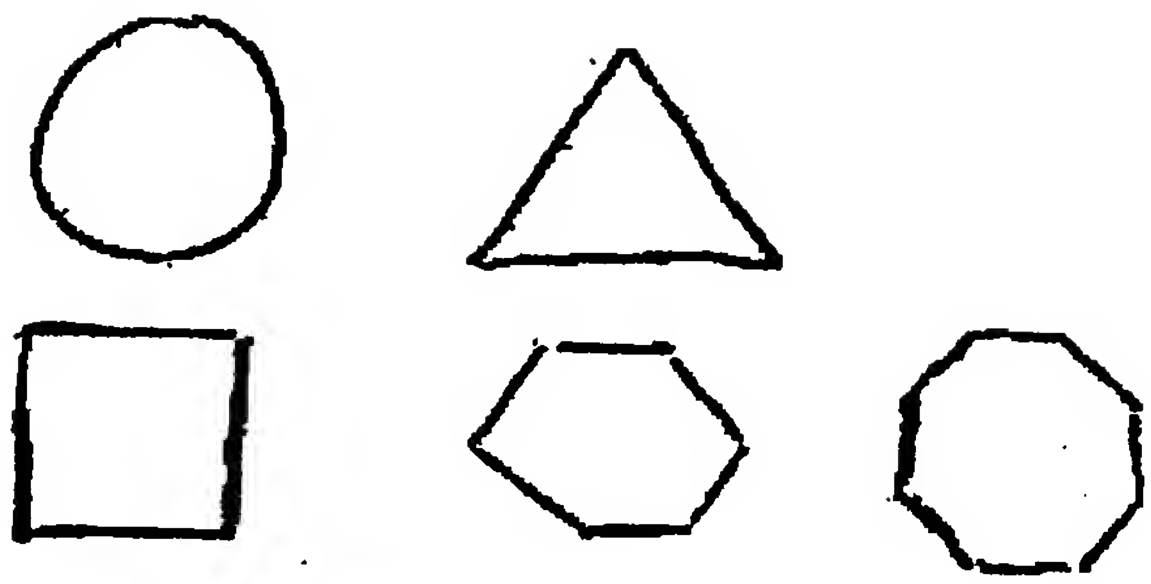

FIGURE 3A

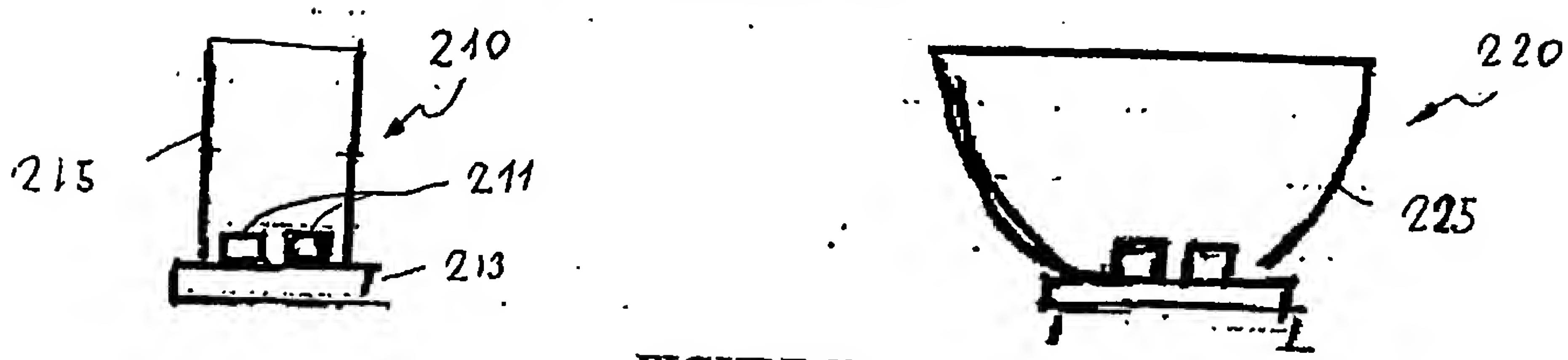

FIGURE 3B

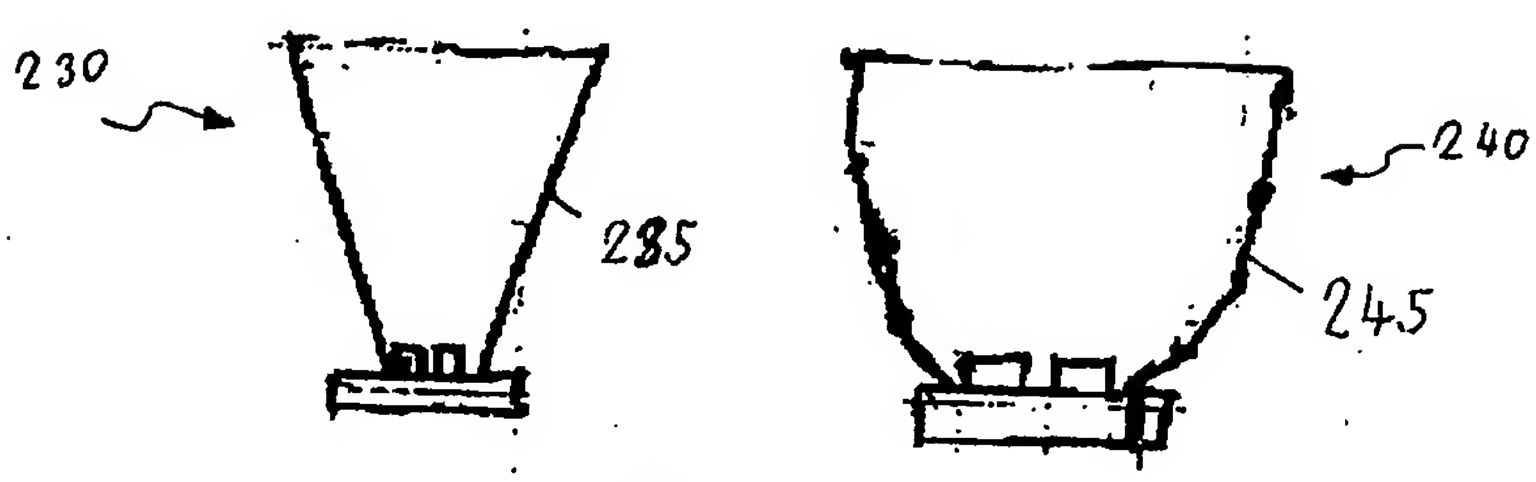

FIGURE 3C

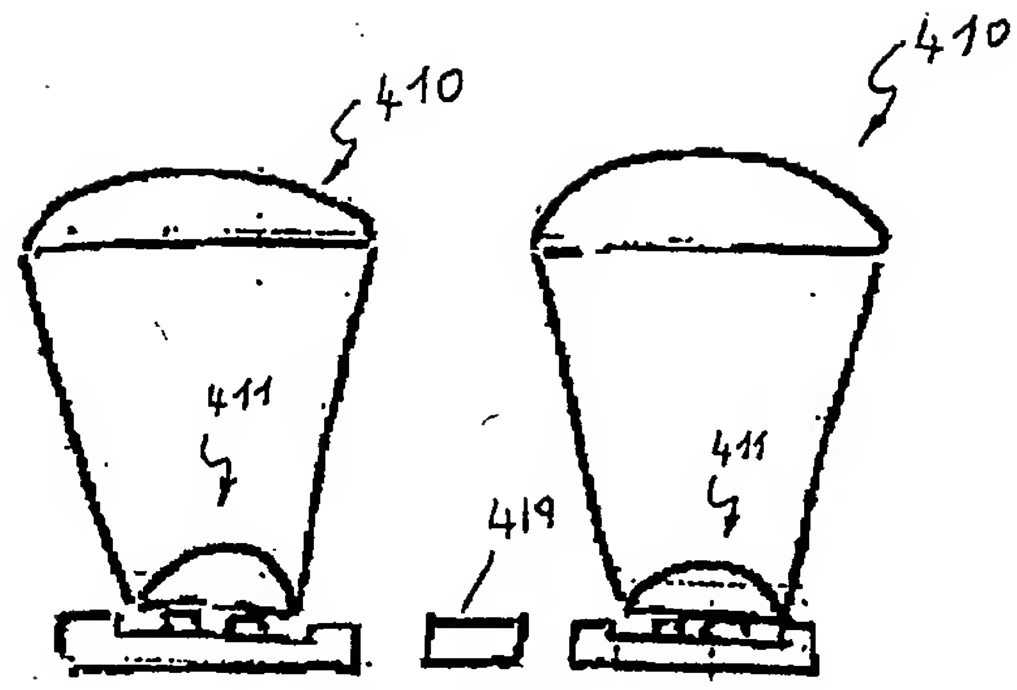

FIGURE 4A

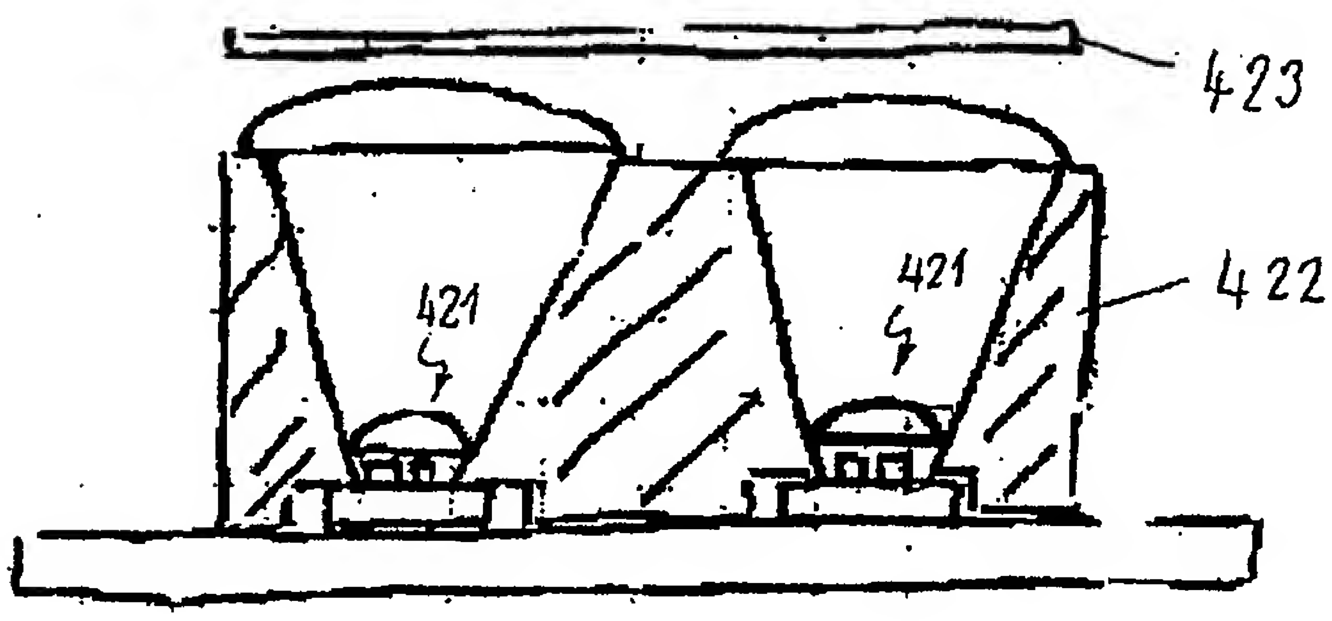

FIGURE 4B

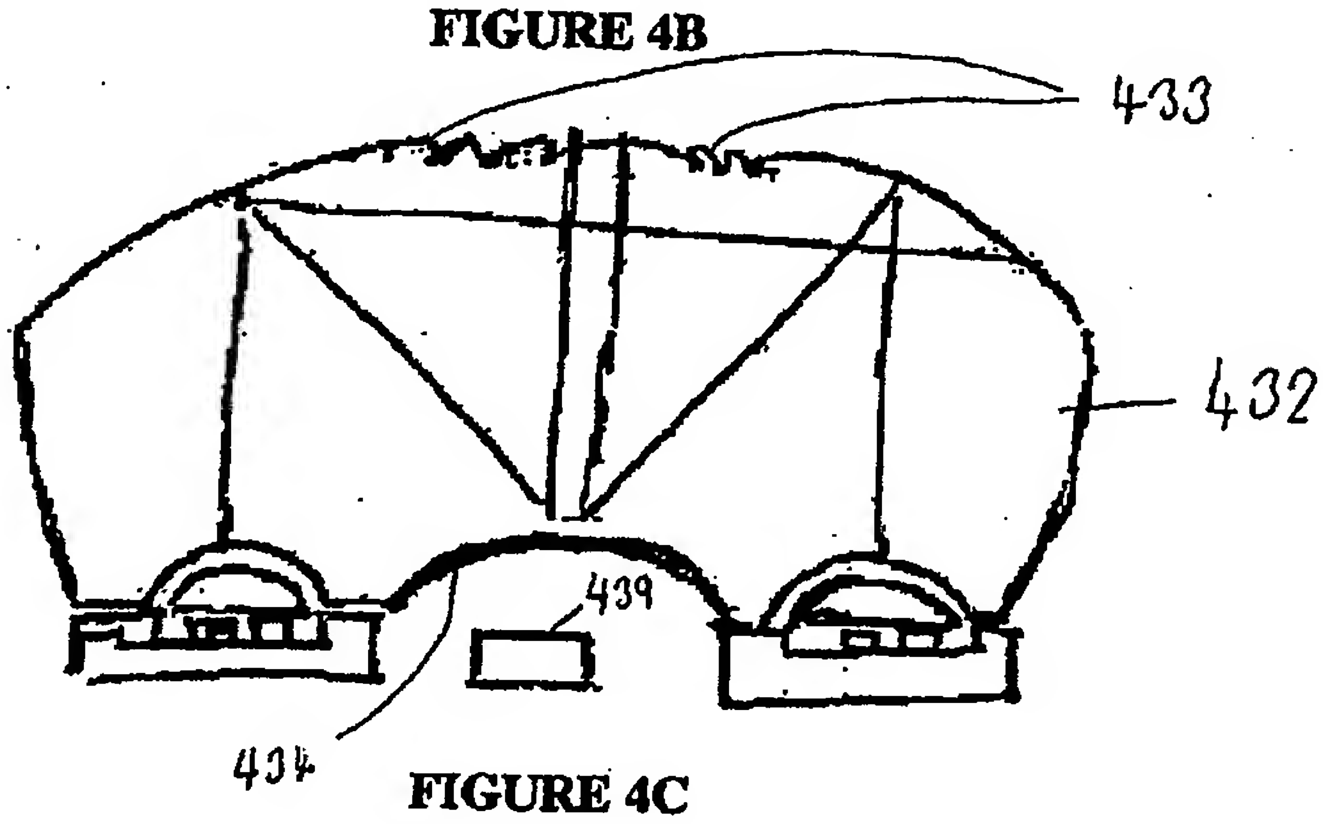

FIGURE 4C

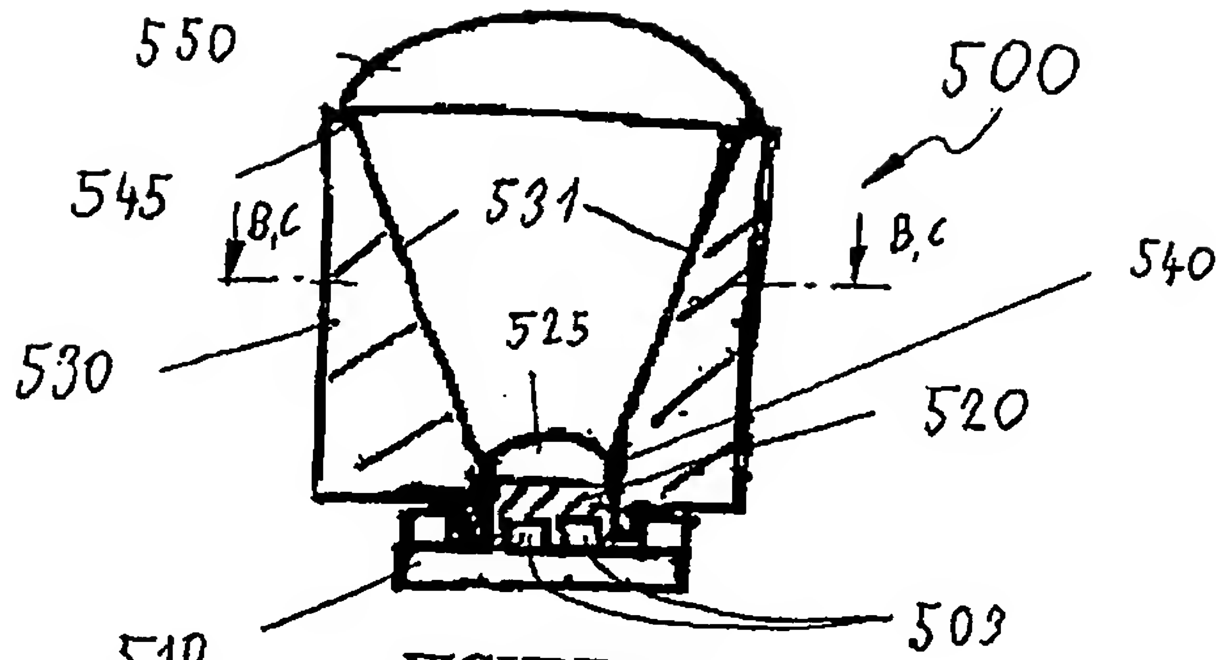

FIGURE 5A

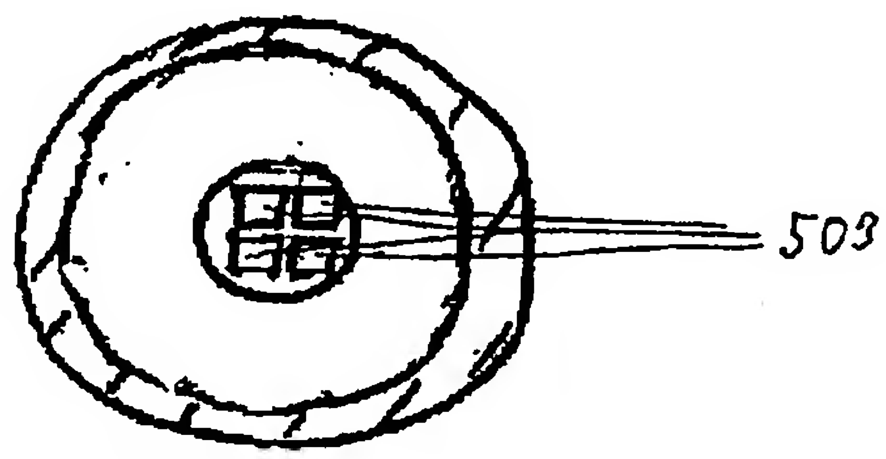

FIGURE 5B

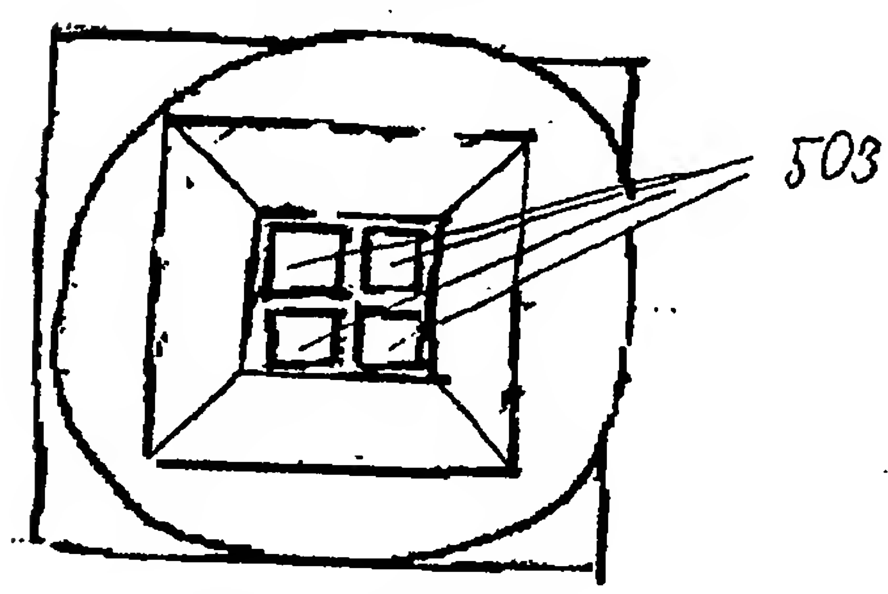

FIGURE 5C

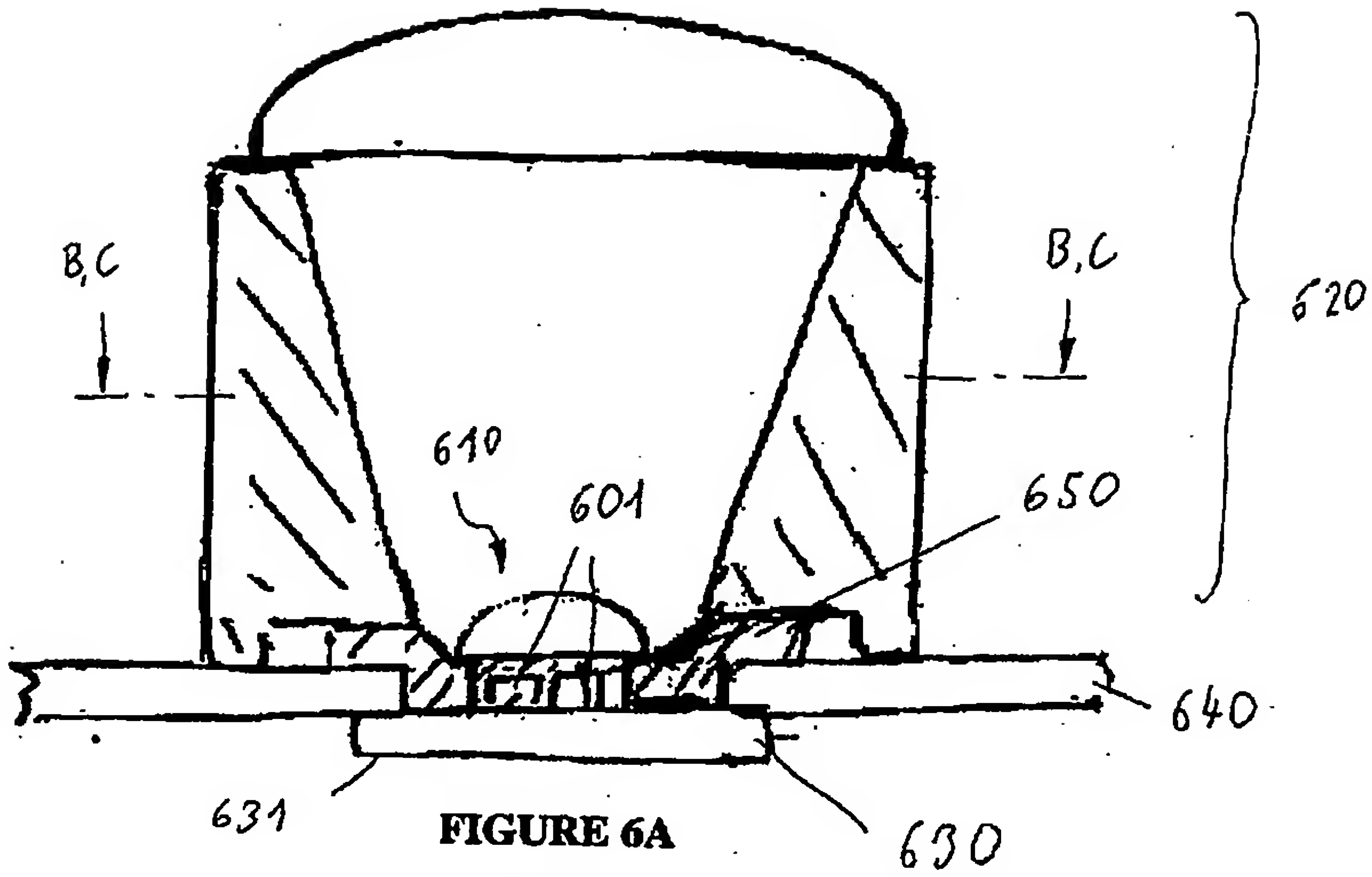

FIGURE 6A

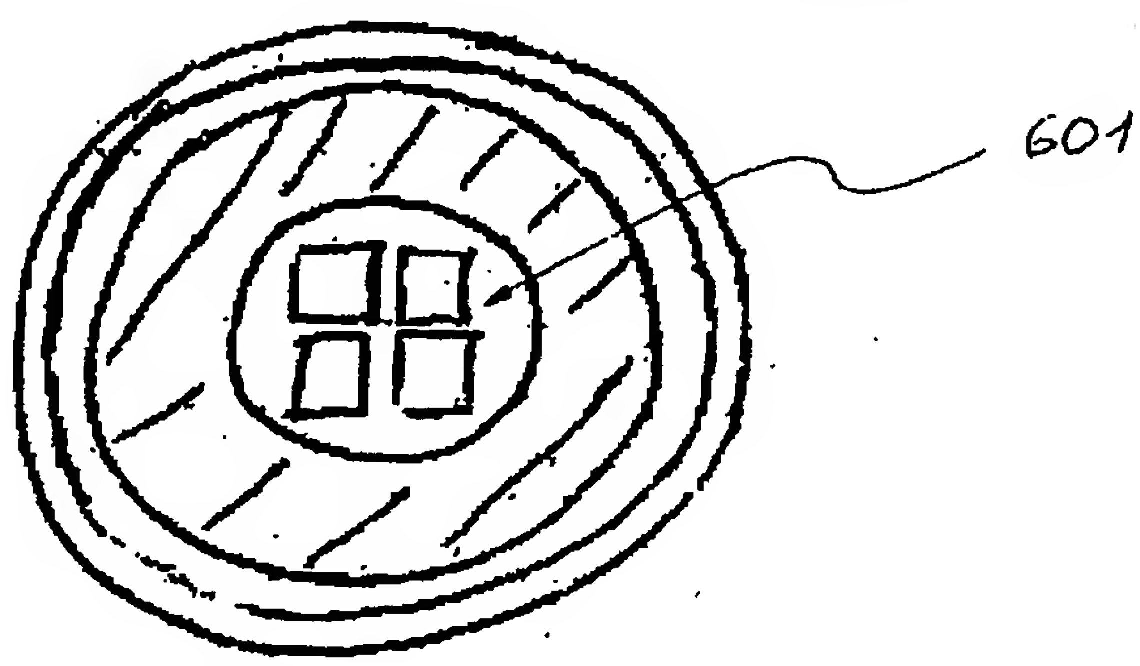

FIGURE 6B

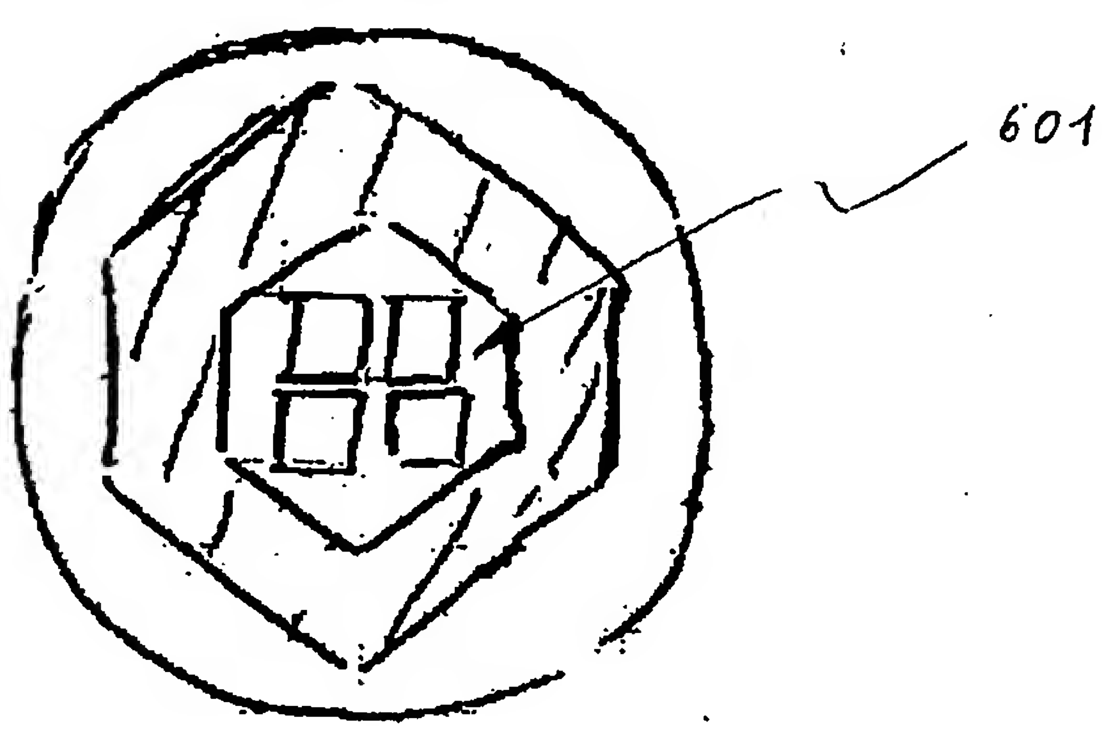

FIGURE 6C

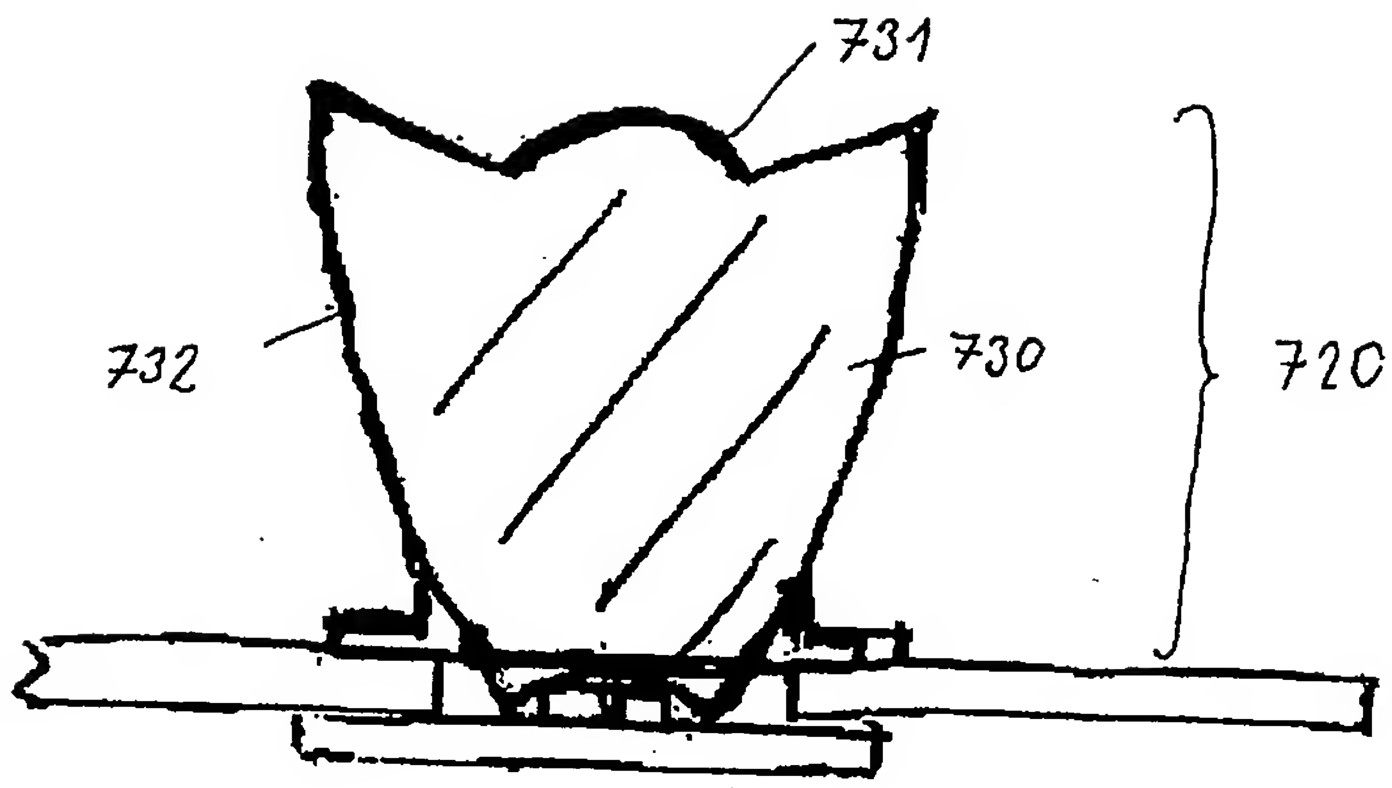

FIGURE 7A

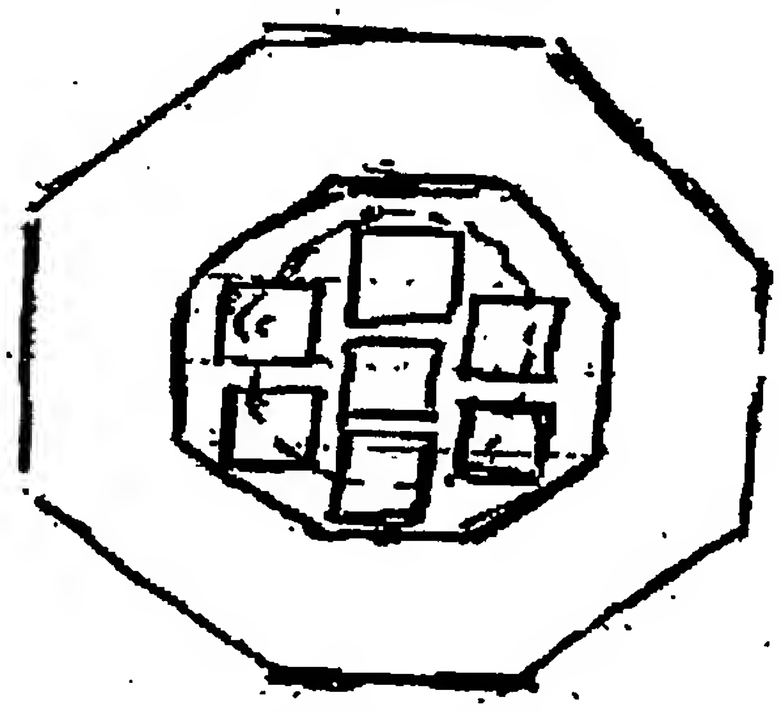

FIGURE 7B

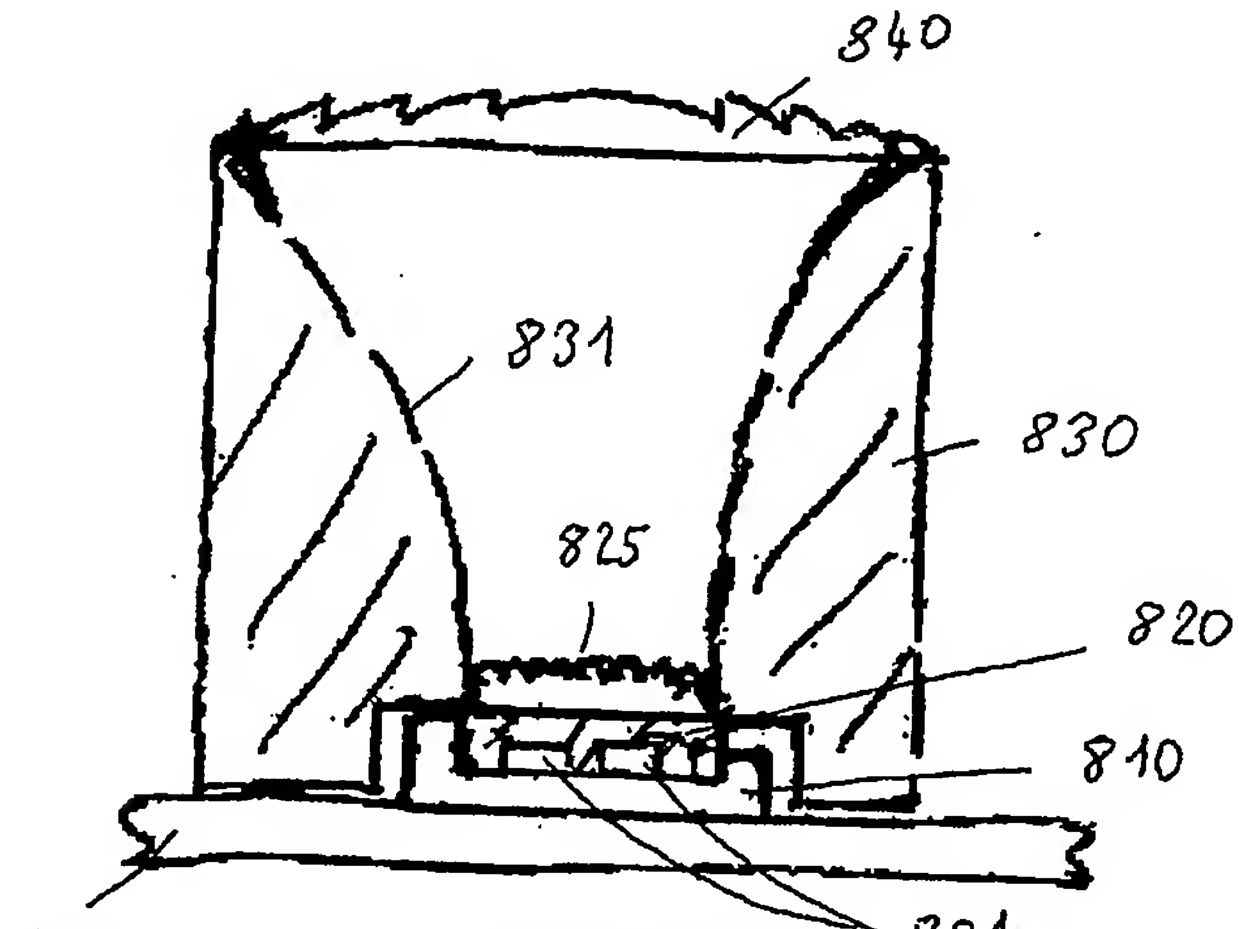

FIGURE 8

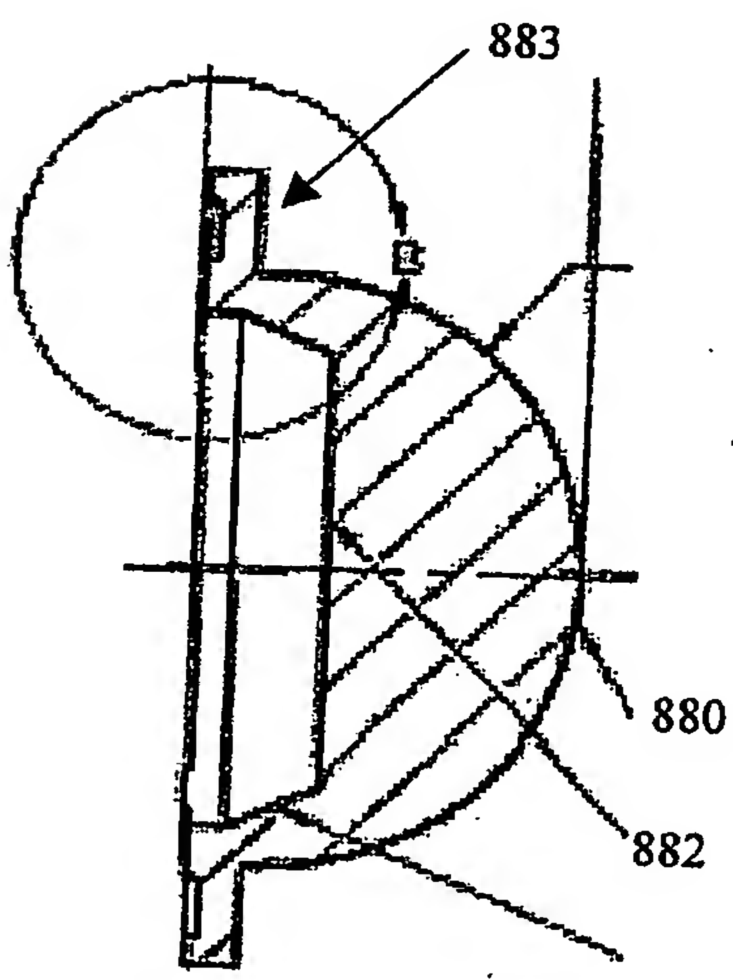

FIGURE 9

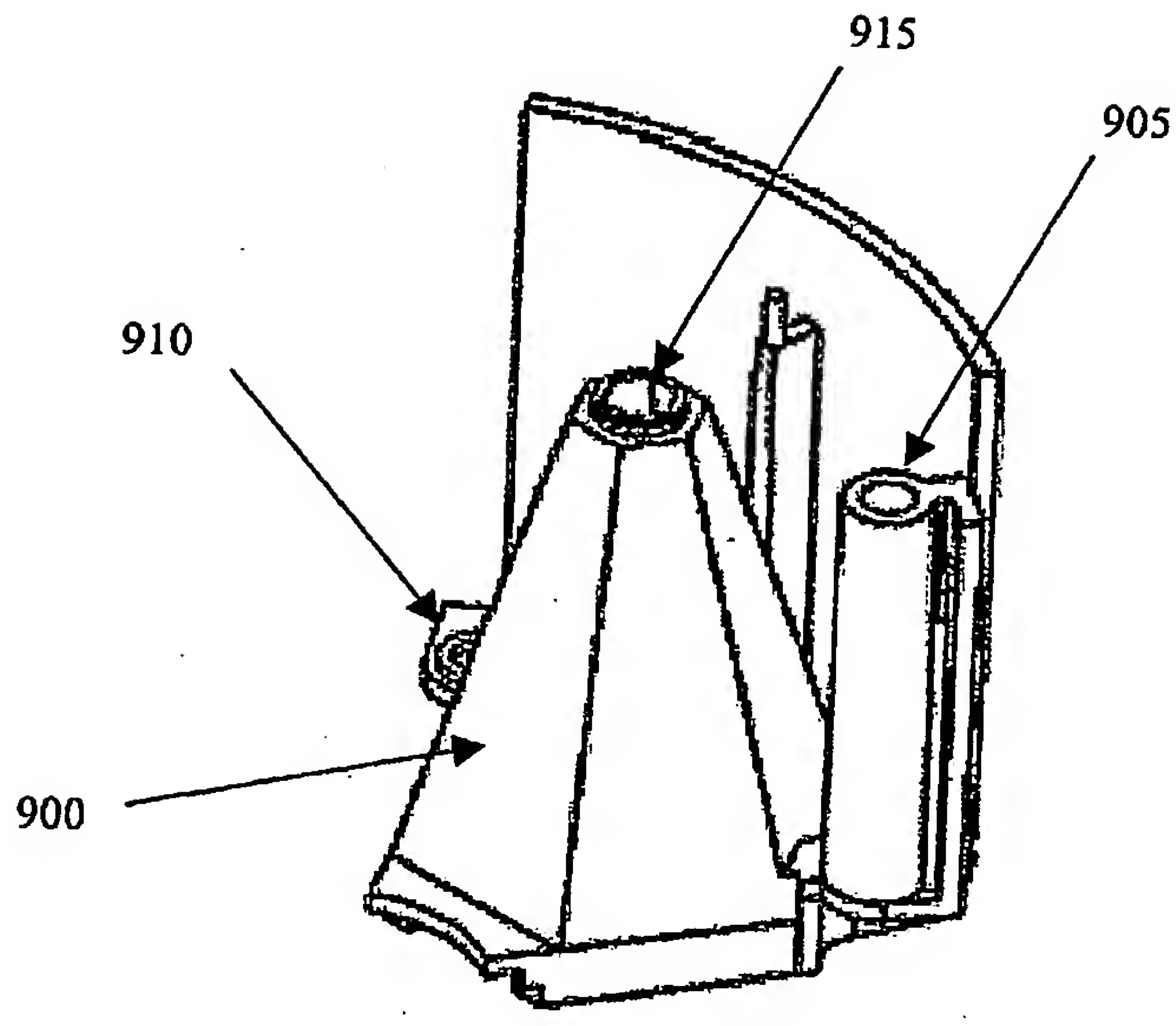

FIGURE 10

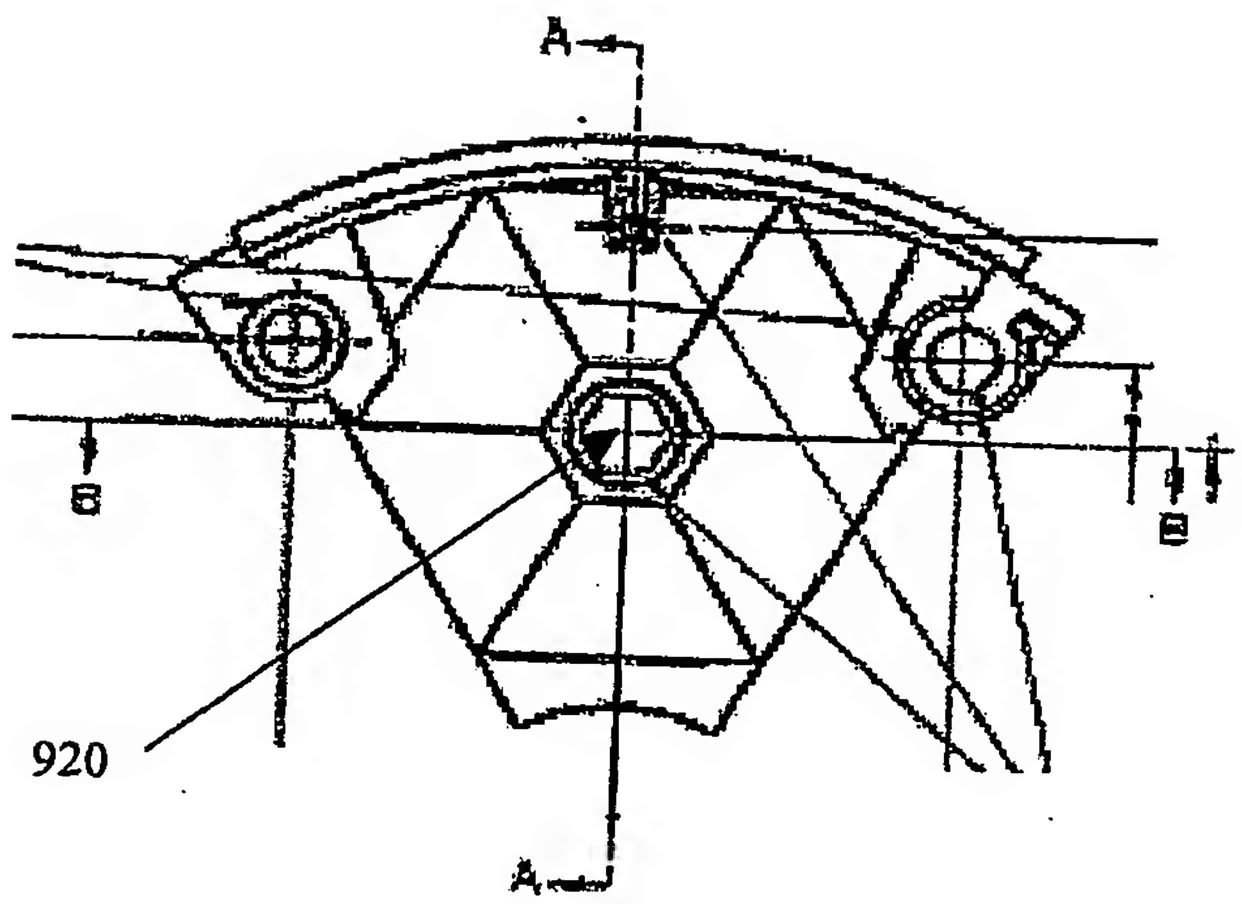

FIGURE 11A

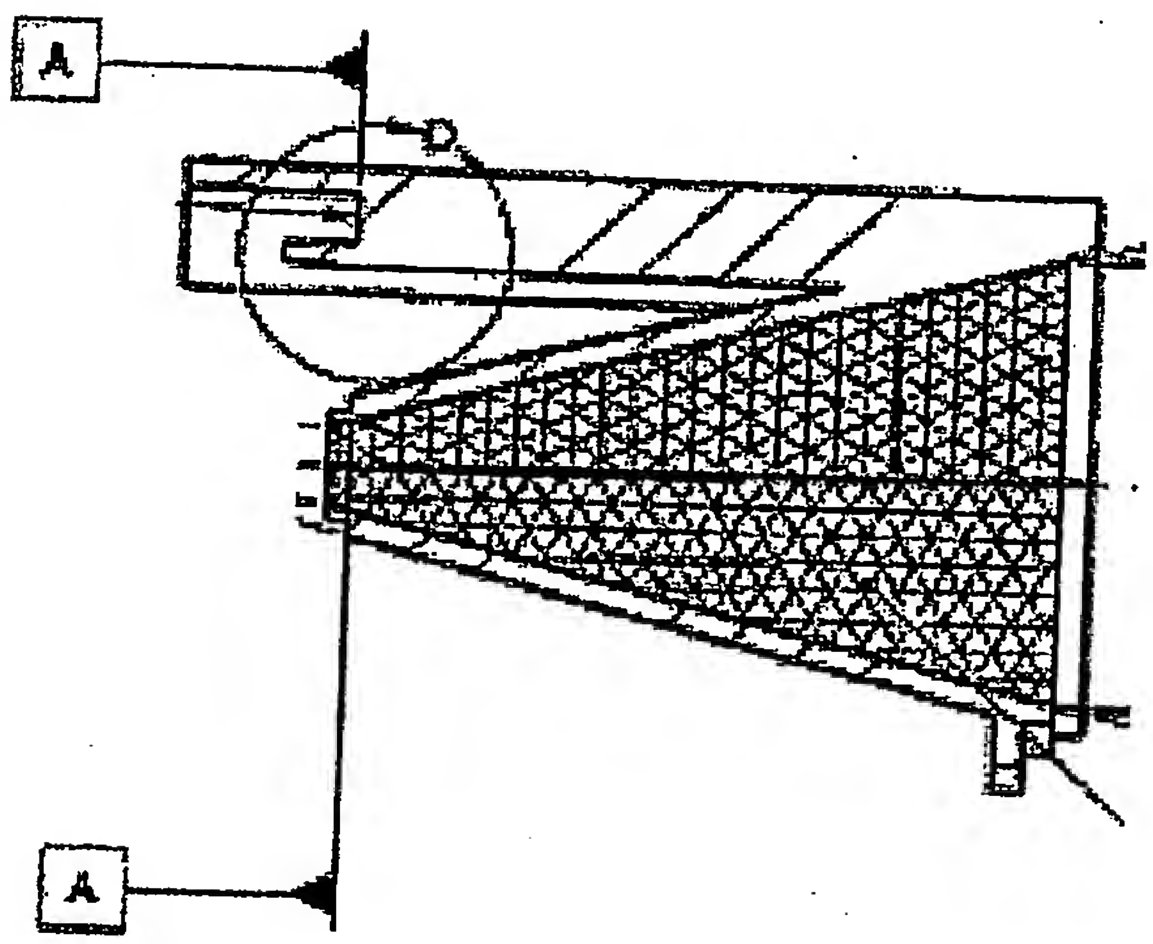

FIGURE 11B

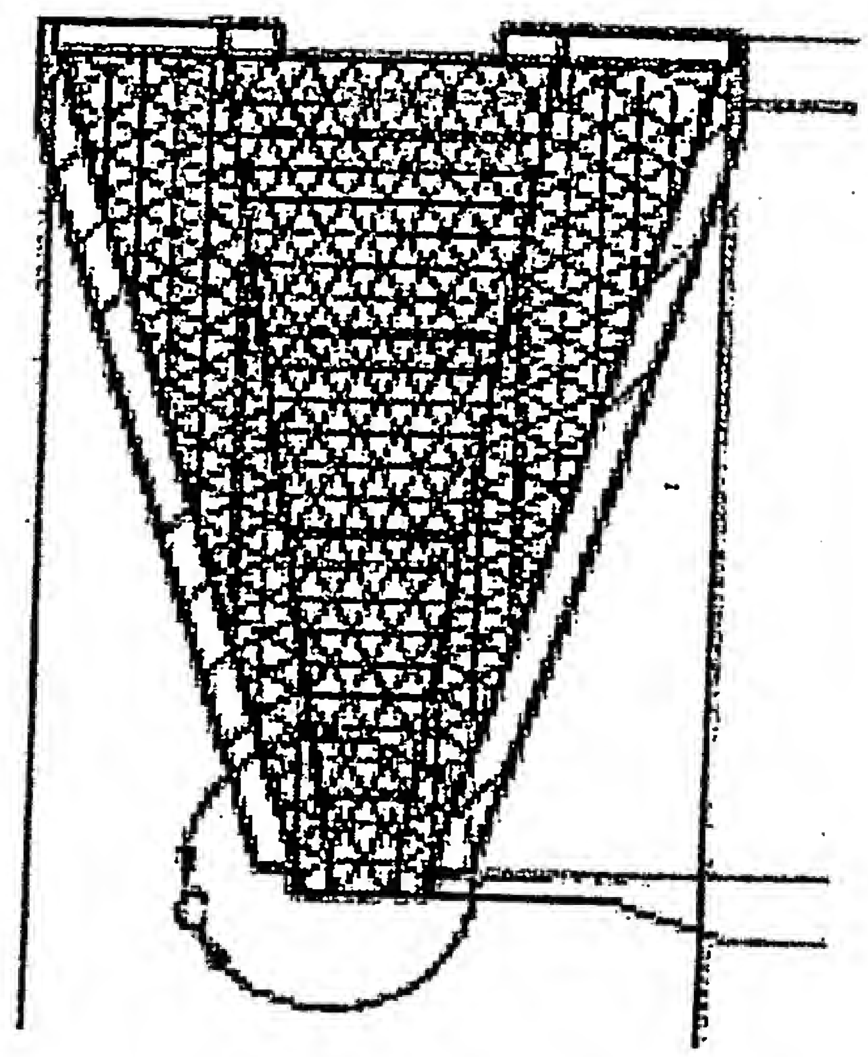

FIGURE 11C

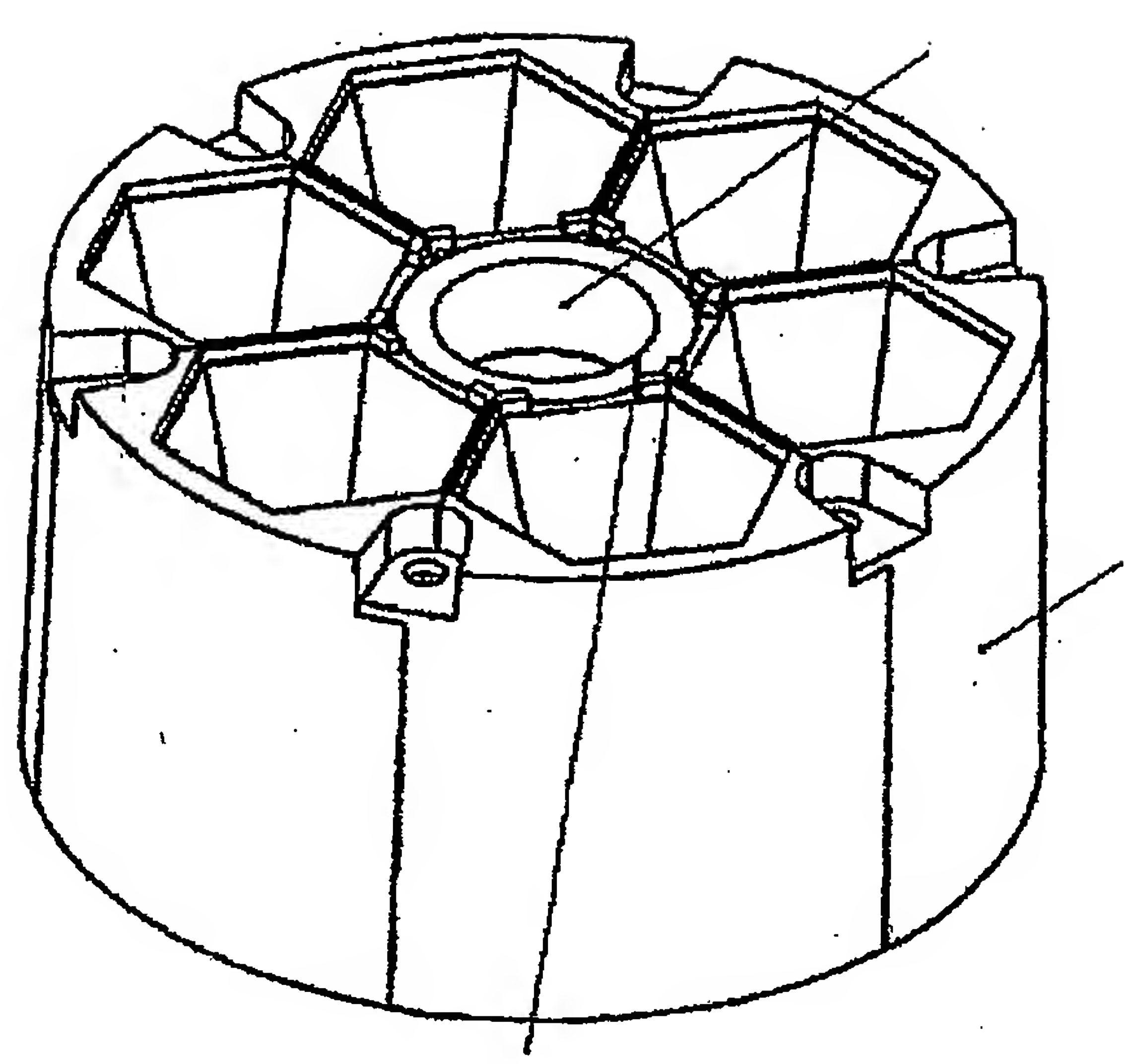

FIGURE 12

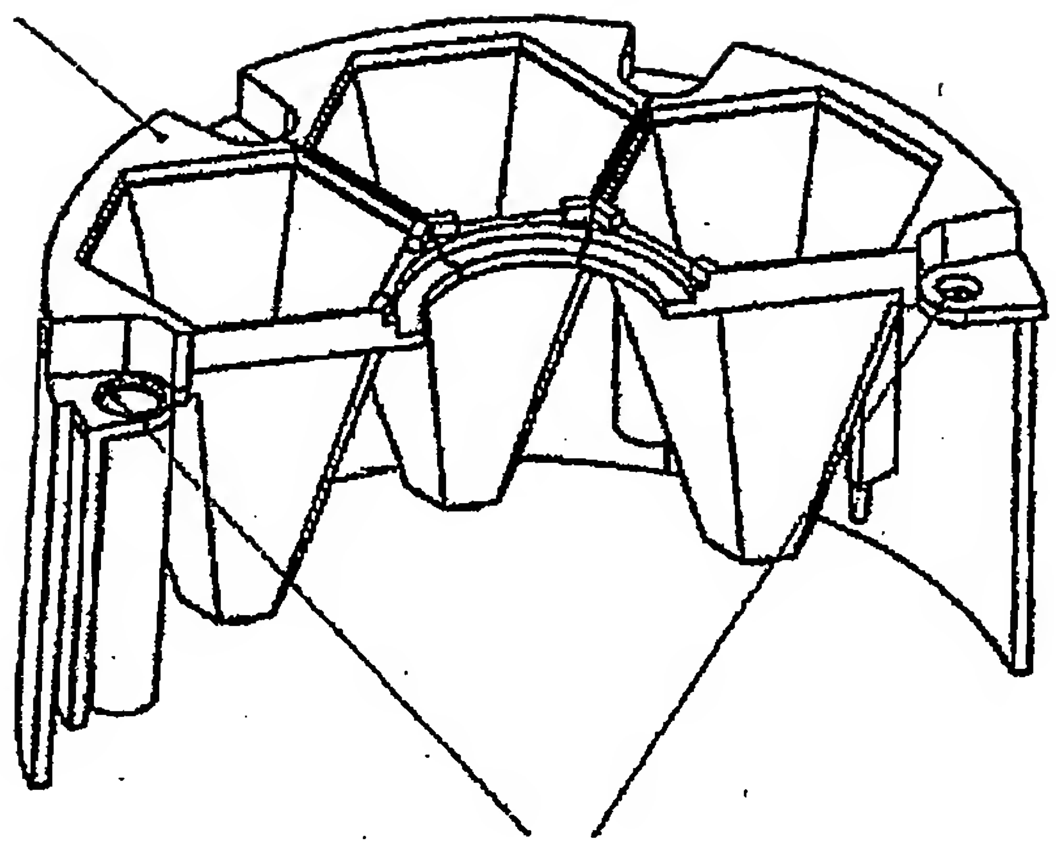

FIGURE 13

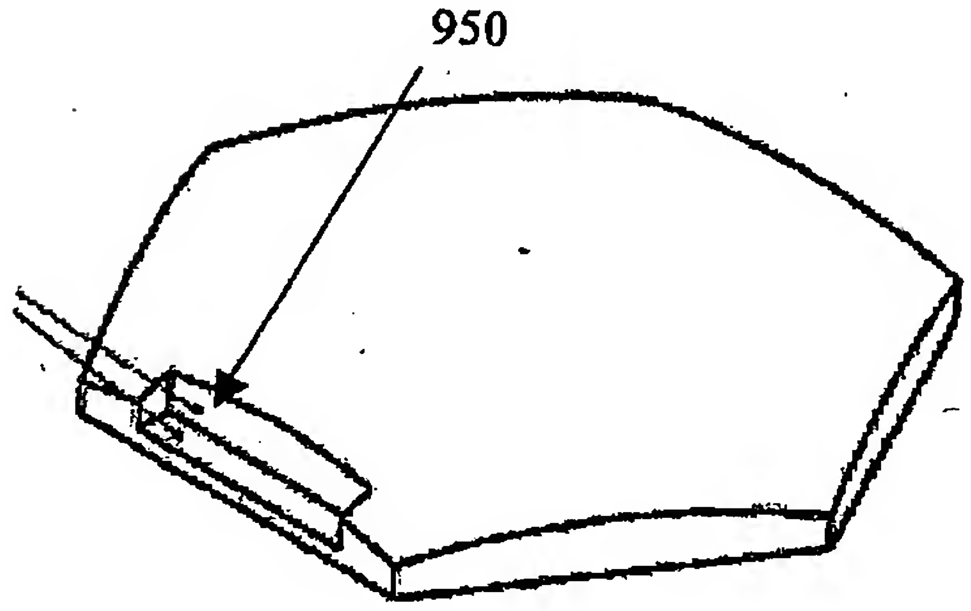

FIGURE 14

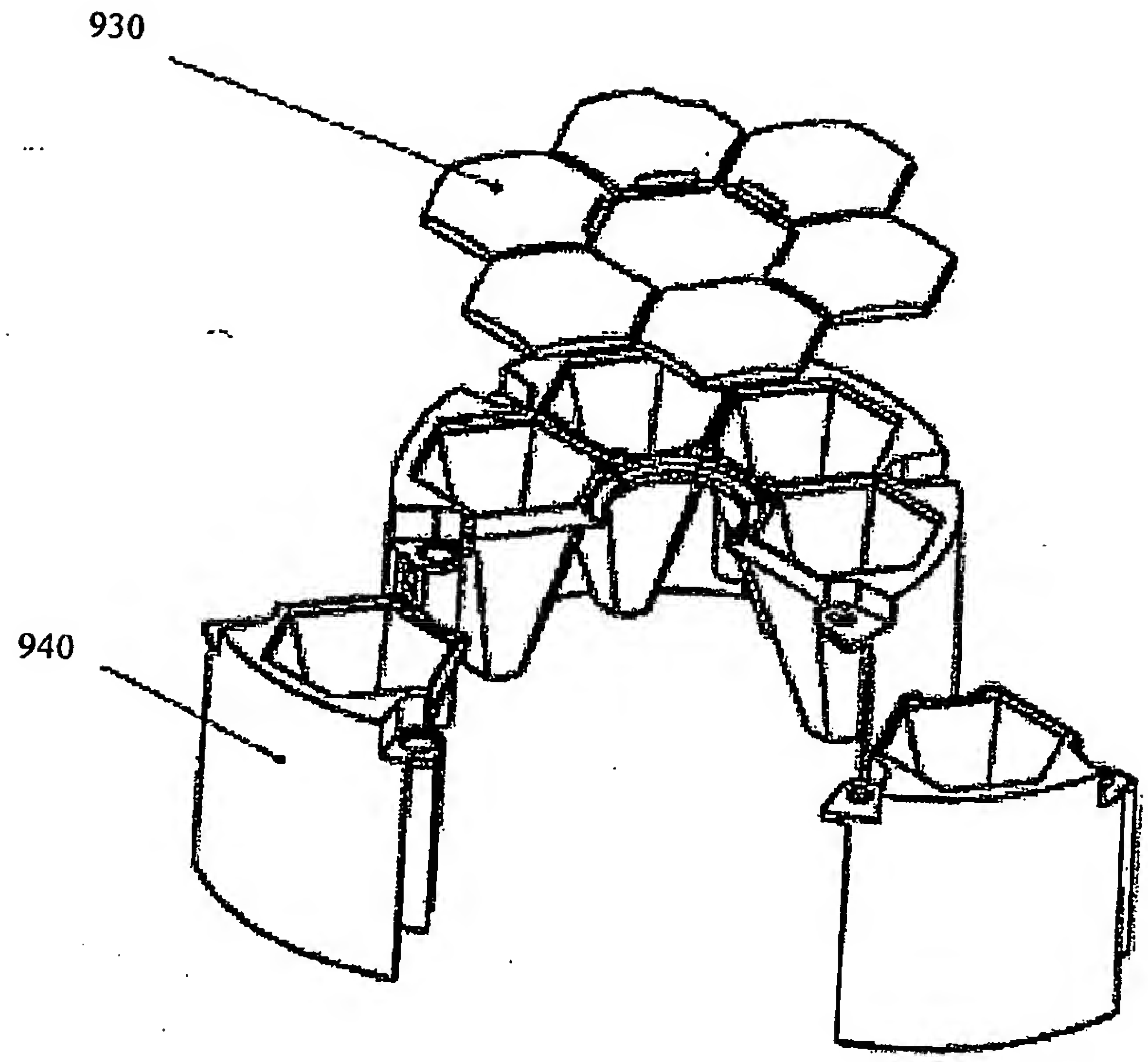

FIGURE 15